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Review of historical and new monitoring data for geotechnical subsidence assessment at San Manuel and Kalamazoo block cave mines

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Abstract

San Manuel and Kalamazoo historical mine operations have been formally closed since 2003 with significant efforts to decommission infrastructure and establish long-term landforms, along with other key activities. The adjacent mining units are located in Arizona, United States.

Monitoring and ground control management of the open pit and surface above the former block caves is a continued mandate of the closure asset team for regulatory compliance. During and following mining, observable subsidence features have formed and radiated around the underground footprints. The geometry of these features has been defined by the underlying geology and rock mass conditions, block cave progression and the excavation of an open pit through earlier subsidence at San Manuel. In recent times displacement may not be observable to visual inspection but can be detected by some monitoring techniques.

This paper presents a case study evaluation of the subsidence features and their possible long-term behaviour using historical and new monitoring data. The study highlights the appreciable gaps in the geotechnical data and monitoring record, and the attempts to maximize understanding through publicly available aerial imagery. Important data sources (i.e., development plans, crack mapping) and monitoring techniques (i.e., drone surveys, InSAR) are each examined with regards to the required precision, limitation, and the actual value to this evaluation. The datasets were further evaluated to understand post-operation subsidence to verify where the bulk of the displacement has already occurred. The consolidated findings were compared against conceptual block cave behaviour established in industry and empirical break-break relationships.

Keywords: *open pit, caving, subsidence, geotechnical, stability*

1 Introduction

The San Manuel and Kalamazoo mines located in Arizona are historical block cave operations that have been formally closed since 2003 and under post reclamation monitoring and maintenance. Ground control management of the open pit and surface above the former block caves is a continued mandate of the closure teams to meet regulatory compliance. During and following mining, observable subsidence features have formed and radiated out from the underground mines. A map of the closed mining areas showing key surface features are shown in Figure 1.

The objective of the presented case study was to expand the recent subsidence monitoring record, identify trends and predict any long-term displacement geometries toward the property boundaries. The study relied on monitoring data included in historical reports, and new data acquired from aerial imagery, crack mapping, field inspections and InSAR (interferometric synthetic aperture radar) surveys. The study findings were used to refine asset management strategies.

Key findings, advantages and resolution challenges associated with each of the applied monitoring techniques are discussed. The consolidated findings are then compared against empirical subsidence relations with the results presented.

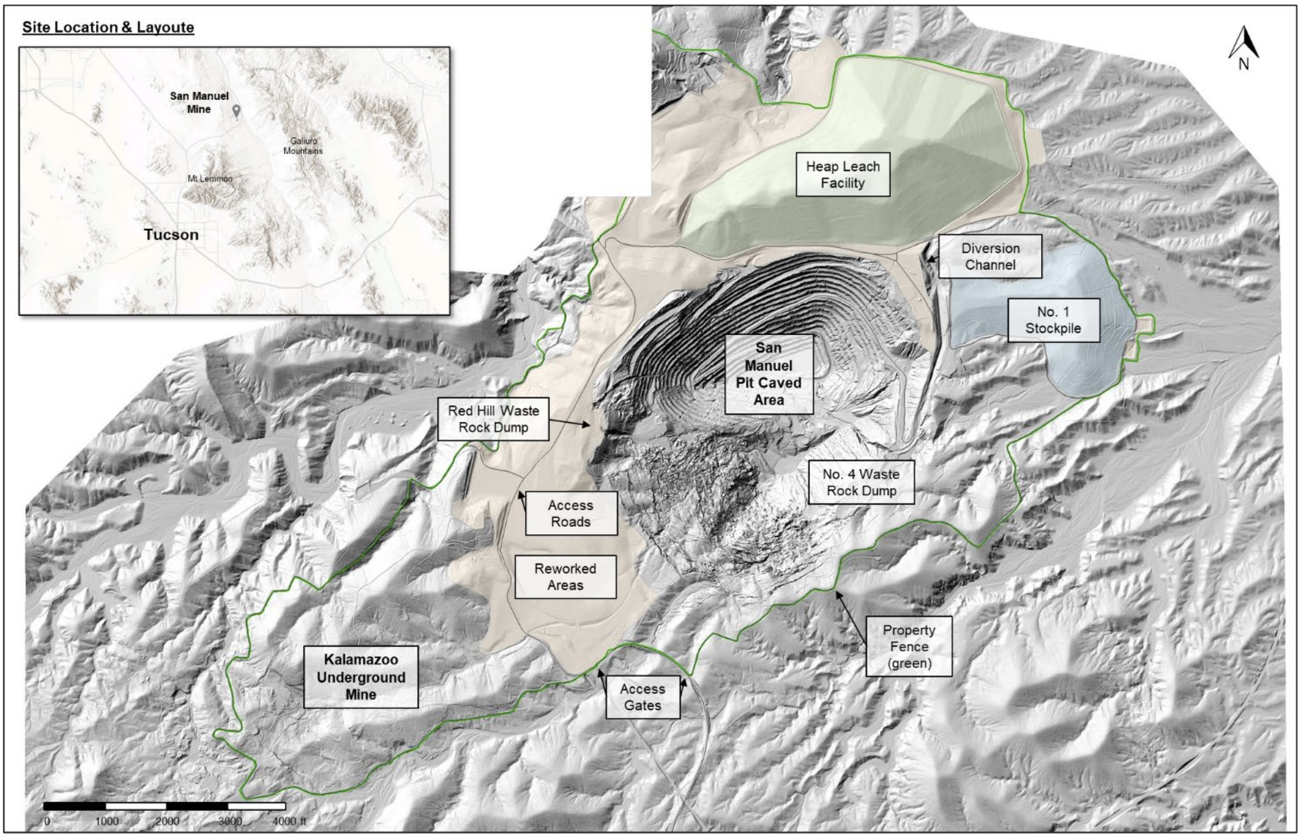

Figure 1 **Current San Manuel and Kalamazoo property layout**

1.1 Block caving induced subsidence

Subsidence above a block cave mine occurs when sufficient material has been extracted to cause the crown pillar to fail allowing material from the surface to move into the voids created through mining. Factors that influence cave-induced subsidence have been described by many authors (Flores & Karzulovic 2003, Laubscher et al. 2017, Woo et al. 2013, Stegman et al. 2018). These factors can include:

- Topography
- Ore body characteristics (i.e., geometry, inclination)
- Rock mass conditions
- Structural geology
- Open pit excavation
- Mining (i.e., undercut level, production rates, draw rates)

Flores & Karzulovic (2003) stated that topography and structural geology can be ranked higher in importance to define subsidence behaviour. Subsidence can be asymmetric due to the ore-body geometry contributing to differing angles of break between the hanging wall and footwall (Woo et al. 2013). This asymmetric behaviour can be observed for San Manuel but less so for Kalamazoo. Subsidence features can be classified into crater (mobilized), fracture or continuous subsidence zones (Figure 2).

The post-caving monitoring phase can be characterized by time-dependant compaction of broken material within the mobilized cave zone (Resolution Copper 2020). Reported industry case studies indicate that the incremental change in subsidence reduces rapidly following cessation of ore drawing operations. An important aspect for Kalamazoo is the intact crown-pillar that has not fully developed due to the interruption of mining in 1999.

An example of the large-scale cracking with the San Manuel crater and fracture zone are shown in Figure 3a. Smaller linear features are observed within the continuous subsidence zone as shown in the Figure 3b example. Importantly for the San Manuel deposit is the removal of restraint as the open pit was excavation through the oxide materials within the crater zone.

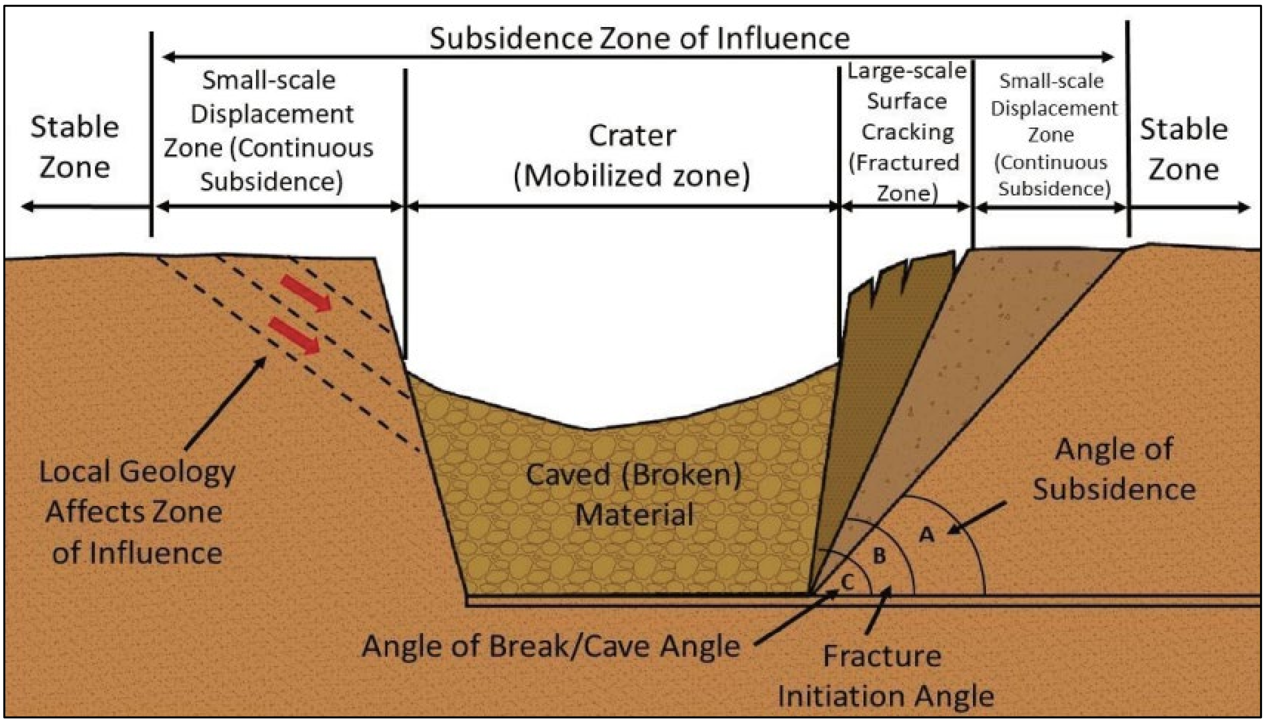

Figure 2: Block cave subsidence terminology, modified from Laubscher et al. 2017

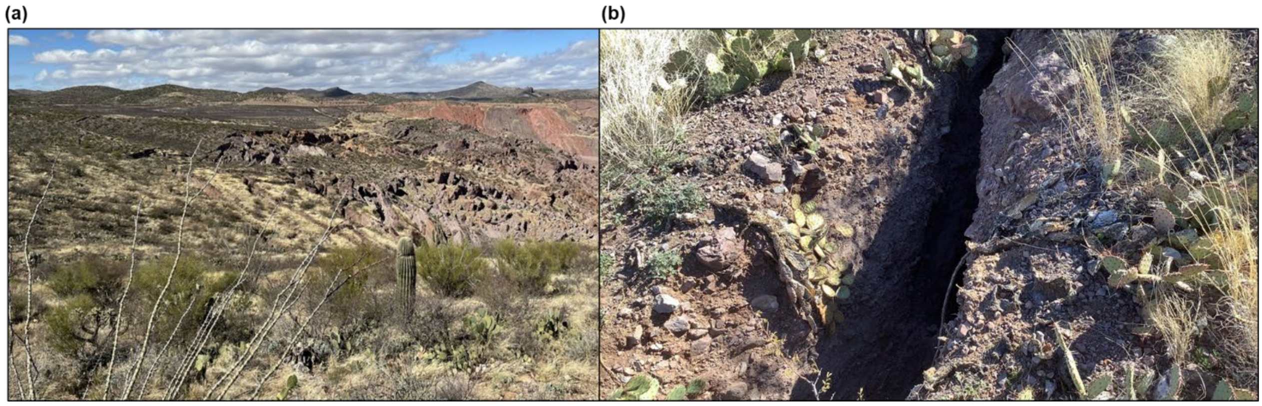

Figure 3 (a) Subsidence crater above the San Manuel block cave within the fracture zone and (b) Example of subsidence crack propagated up through the surficial quaternary soils

1.2 Historical operations

The deposit has an extensive history of exploration and mining operations dating back to the 1870s. Main activities that are relevant to reclamation and monitoring occurred between 1944 to 2002. Mine operations ceased 1999 and heap leaching activities ceased in 2002. Permanent mine closure was announced in 2003. Interaction of the operations and deposits over the past century is shown in Figure 4.

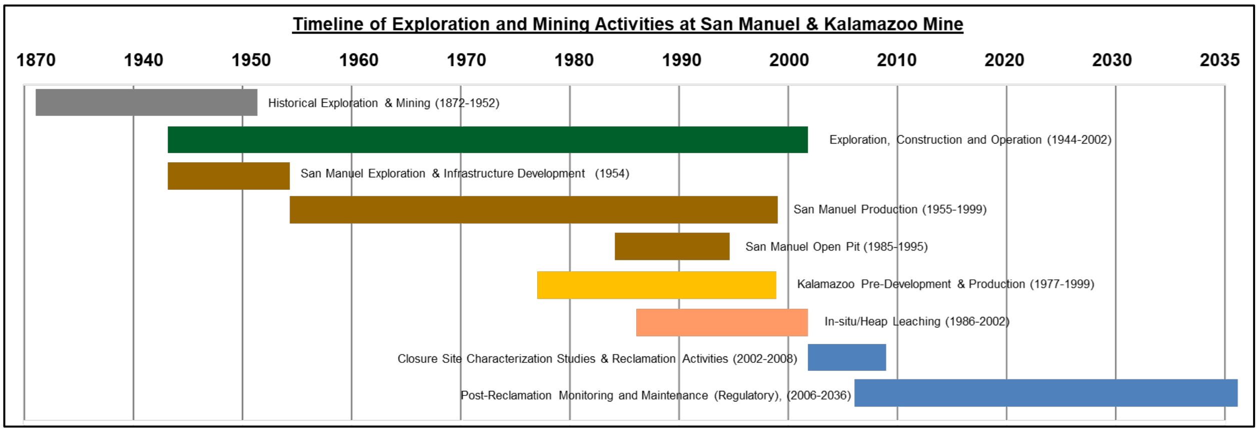

Figure 4 Timeline of mining activities and ownership at San Manuel and Kalamazoo Mine

The mine consists of two structurally divided deposits that were operated as two distinct mines. San Manuel comprised a sulphide copper underground block cave mine and an oxide copper open pit mine, heap-leach, and in-situ leach operation. The San Manuel undercut levels are shown in Figure 5. The Kalamazoo mine is a sulphide copper underground block cave to the southwest (Figure 1).

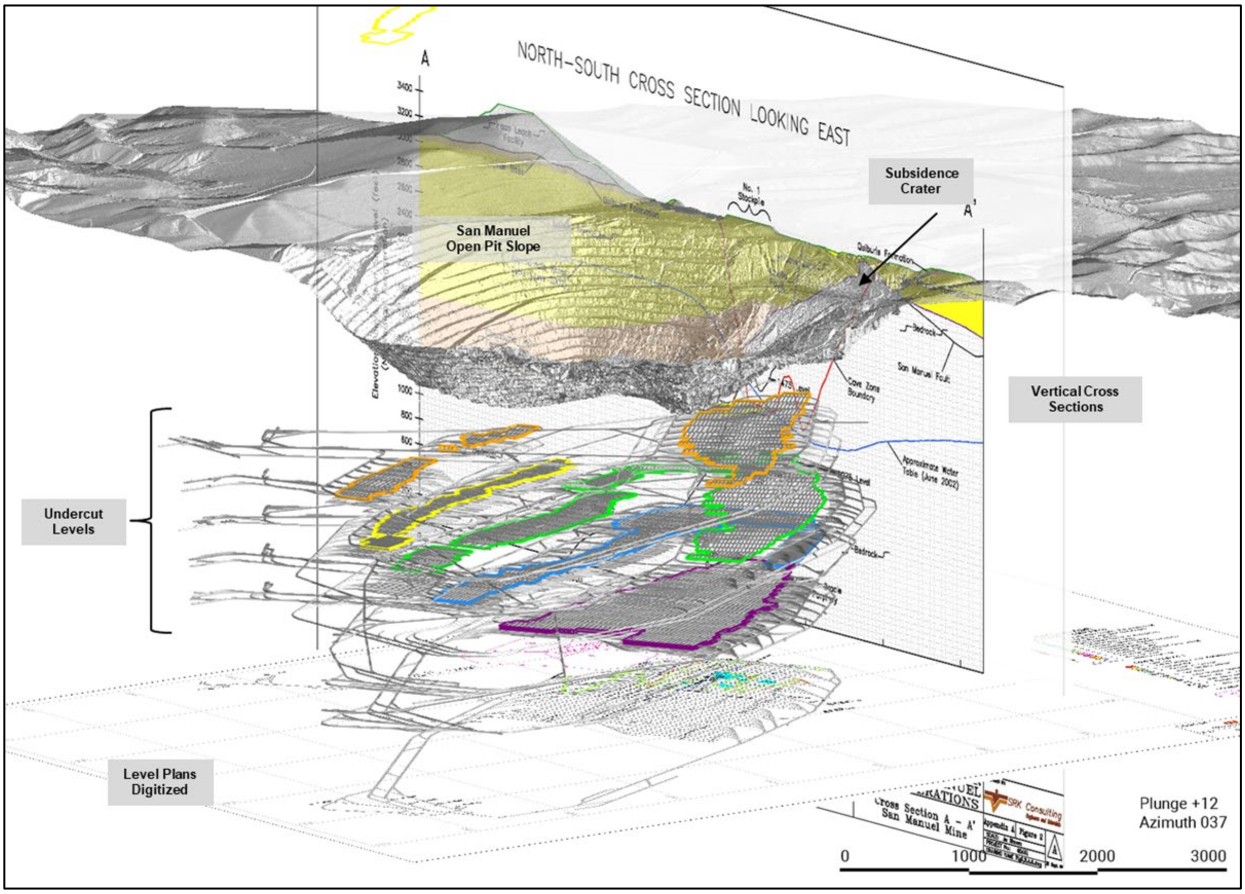

Figure 5 **Undercut levels at San Manuel below the open pit and subsidence crater (SRK, 2019) and digitized plan and vertical sections from historical records**

2 Geological and structural geology context

The orebody situated within Precambrian-aged oracle granite (quartz monzonite) and diabase dikes, and cretaceous-aged monzonite porphyry (granodiorite). During the Tertiary, extensional faulting rotated the deposit to the northeast and displaced the hanging wall (Kalamazoo) orebody down dip about 8,000 ft from the footwall (San Manuel) portion. The Cloudburst Formation (alluvial conglomerate and interbedded volcanics) was deposited concurrently with the tilting. The San Manuel Formation (conglomerates and sandstones) was deposited disconformable above the older formations. A geological cross section is shown in Figure 6a.

Geological model resolution challenges identified in the study include:

- Geological drilling data was sparse toward the current property boundaries.
- No 3D lithological interpretations and updates have been made to reflect the post-operational surface deformation and cave developments.
- Structural geology interpretations were limited to deposit continuity and primary faults while secondary faults were neither interpreted nor modelled. There were limitations to correlating surface displacement to faults or identifying major features that limits and bounds the subsidence zones.
- Changes in thickness or geometry in the overlying San Manuel Formation have not been identified to correlate any far-field displacements near the fence and property line.

3 Case study approach

Detailed historical records from 1955 to 1970 were used to establish early subsidence behaviour during San Manuel production (Figure 6b). Through an early data compilation phase, it was identified that there was a significant monitoring gap between 1970 to 2018.

The current monitoring snapshot (representing 2018 to 2022) was acquired from aerial imagery, crack mapping, field inspections and InSAR surveys. With consideration to the historical monitoring gap, United States Geological Survey (USGS) aerial imagery was acquired to understand recent subsidence trends near property boundaries and to establish a current baseline. Subsurface instrumentations were not installed as part of this study, instead, surface displacement findings were compared with empirical tools (i.e. Laubscher, et al. 2017).

4 Subsidence monitoring data evaluation

There are many surface and subsurface monitoring techniques available to understand displacements through operation and into closure. The applicability of different techniques may change over time, including the monitoring frequency as the cave develops and surface cracking radiates away from the undercut levels (Figure 2). Some monitoring techniques are briefly described in Table 1.

4.1 Historical reports, plans and sections

Monitoring data from historical reports, plans, and sections were compiled (Figure 5). The historical data was limited to the early production stages. Important learnings from the historical data include:

- Source and accuracy of historical data varied significantly. Due to the significant changes in technology and data resolution, it was difficult to generate continuous data sets over the 50+ years of operation and to make appropriate interpretations.
- Production rates and cave developments were not recorded to the level of detail to correlate with recent monitoring data. For Kalamazoo, only a small footprint of the original plan was developed, however, there little to no data on how much material was drawn.
- Historical mine plans, typically hand drawn, were difficult to digitize and time consuming to geo-reference. Once complete, the data provided a significantly references especially as todays landforms can be significantly difference that pre-production.

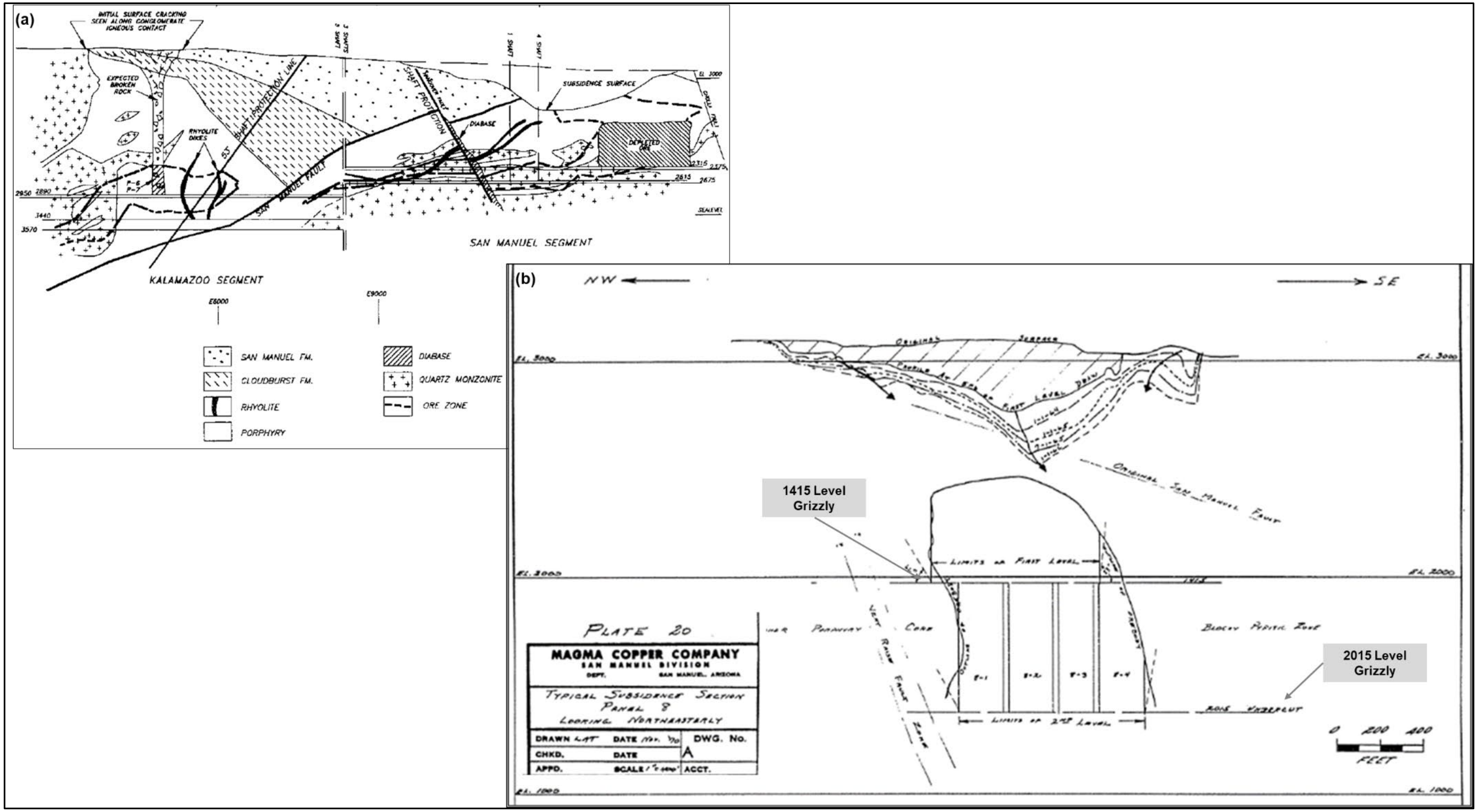

Figure 6 (a) Cross-section through the deposits with asymmetric subsidence shown (Sandbak et al. 1995) and (b) Early San Manuel subsidence above 1415 and 2015 grizzly levels (modified from Thomas 1971)

Table 1 Monitoring technique summary

Target	Technique	Type	Objectives
Surface	Terrestrial	Survey pins, GPS stations, settlement monuments	Terrestrial survey monitors vertical and lateral surface displacements. Can be positioned in an array to capture wider displacement trends near known cracks.
		Prisms (and total stations)	Surveying prisms from a seasonal total station position.
		Extensometers	Wireline and multi-point tools positioned on either side of features to measure lateral surface displacement.
	Remote	Aerial Photographs	Imagery showing observable changes in landform.
		LiDAR and Aerial Photogrammetry (i.e., Drone)	Digital survey records to detect surface displacements. Processing software can assist with change detections of repeated surveys that are assisted with ground control points.
		Interferometric Synthetic Aperture Radar (InSAR)	Satellite measurements of surface displacements across larger scale area. Resolution of the measurements based on line-of-sight.
Subsurface	Terrestrial	Time Domain Reflectometers, Inclinometers, Shape Arrays	Subsurface instruments to monitor soil and rock mass deformations along a borehole.
		Borehole Camera	Repeated camera surveys in open holes to identify changes in borehole stability and new sidewall fracture features.
	Remote	Smart markers	Radio frequency communication between sensors to monitoring material flow movements and cave propagation.
		Wireless In-Ground Monitoring ("Geo4Sight")	Radio frequency communication between sensors to monitor rock mass deformations with initial installation completed in a borehole.

4.2 Aerial photography

Historic aerial photos taken during the mine's operation were supplemented with aerial photos collected by the USGS from the 1970s to 2018. After 2018, fixed-wing drone surveys were utilized to create high-quality air photos (with a terrain survey). USGS aerial photos were collected across the period from 1979 to 2021. Although varying in image quality, these photos gave insight into the development of the cave and open pit. Photos were georeferenced using surface landmarks (e.g., infrastructure, roads) in Global Mapper (v23.0) and mapped cracks were separated by year.

Four critical subset areas were examined for changes in the subsidence features since the 1970s. An example of the subset evaluation in the south of the San Manuel Mine is shown in Figure 7. In this example no features can be identified until the start of the open pit excavation through the subsidence crater (1984). Most subsidence cracks currently observed in the fractured zone first appeared between 1992 and 2003 aligned to later stages of operation. No new significant subsidence related crack features were identified across the previous 20-year time. Erosion and crest loss can be observed in places along the San Manuel escarpment (Figure 7). However, this is related to ongoing slope instability progression.

Important learnings from the aerial imagery monitoring include:

- Publicly available aerial photography was essential to bridge the data gap between later stage mining and today (post-caving, closure phase).
- Aerial photography can provide reasonable knowledge for the fracture zone extent; however, the resolution is not high enough to detect small changes in the continuous-subsidence zone.
- Digital mapping requires that they photographs are accurately georeferenced with common survey points. The time of day and season can significantly affect shadows which leads to uncertainty in the mapping process, especially when only few images are available.
- It was an effective strategy to create a registry of subsidence cracks. Cracks could be correlated by year and broadly compared with previous appearance or growth descriptions. Areas of uncertainty could be targeted by new drone images and digital/field mapping.
- Where there is uncertainty in the cracks mapped from low resolution aerial images, they should be confirmed with other data sources.
- Historic cracks which were buried during the closure landform reprofiling were in earlier images. Recent images confirmed that cracks have not re-opened.
- Drone surveys can provide high-resolution aerial photos that are repeatable and easily verified. Ground control stations significantly improve the accuracy of the survey.
- Drone flights needed to be completed by a fixed-wing drone due to the significant project area extents.

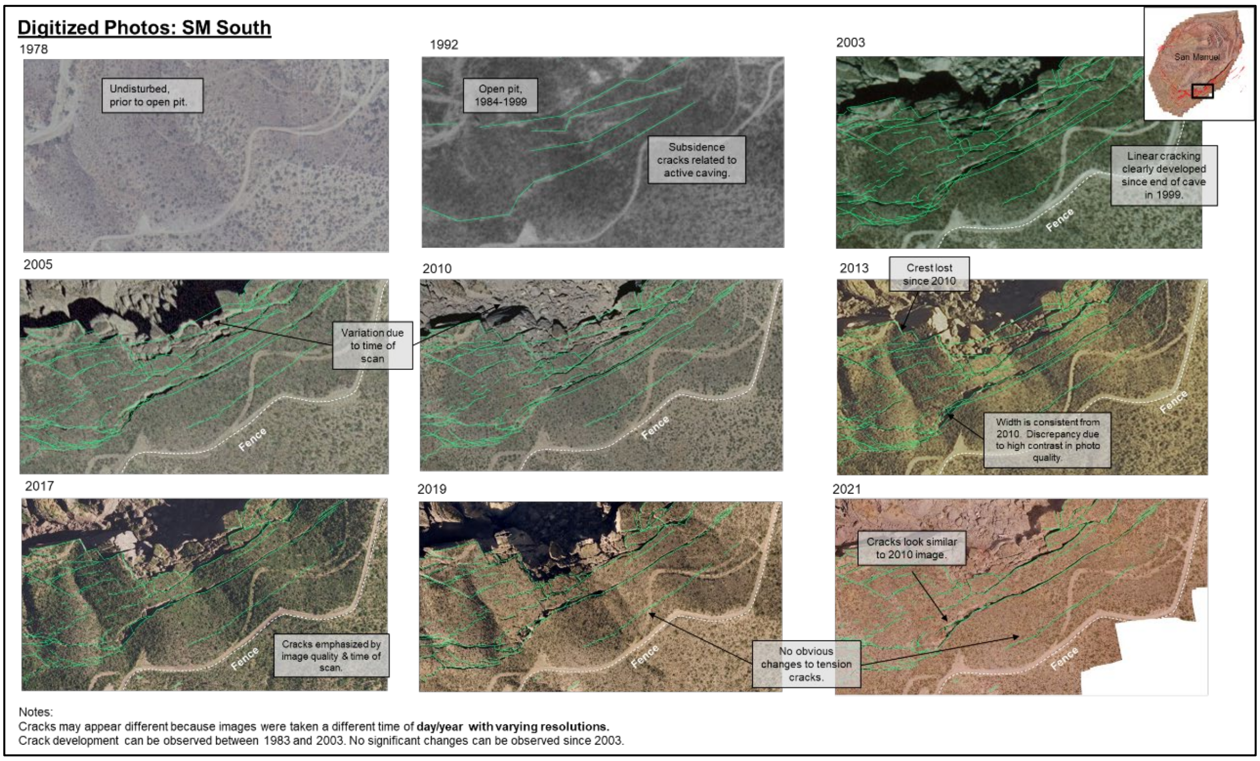

Figure 7 Progress of erosion at San Manuel open pit cave shown as aerial photos from 1978 to 2021 with yearly digitized crack (green)

4.3 Crack mapping

Recent mapping campaigns were completed in 2003, 2004, 2018 and 2021. The compiled database focused on the periphery cracking shown in Figure 8 and Figure 9. The 2018 and 2021 campaigns were verified with field inspections. The features are assigned an ID with observed characteristics such as length, width, and estimated depth. Important learnings from the mapping investigations include:

- Mapping was significantly more time consuming than other monitoring methods. It was not possible to access all areas of subsidence to verify the features.
- New digital/field mapping campaigns targeted specific areas of subsidence using a registry of subsidence cracks from prior air photo interpretations. This allowed areas with prominent level of uncertainty to be targeted and verified.
- Establishing a classification of crack features was critical to distinguishing actual cracks and non-subsidence features that had similar linear trends in air photos. Examples of non-subsidence related features included constructed and natural drainage channels, access roads, sharp boundaries related to historic building foundations, and settlement in former landfill sites.
- Extensive operational and closure experience is held by the asset management teams. Local context and historical observations were able to be integrated with the monitoring data findings.

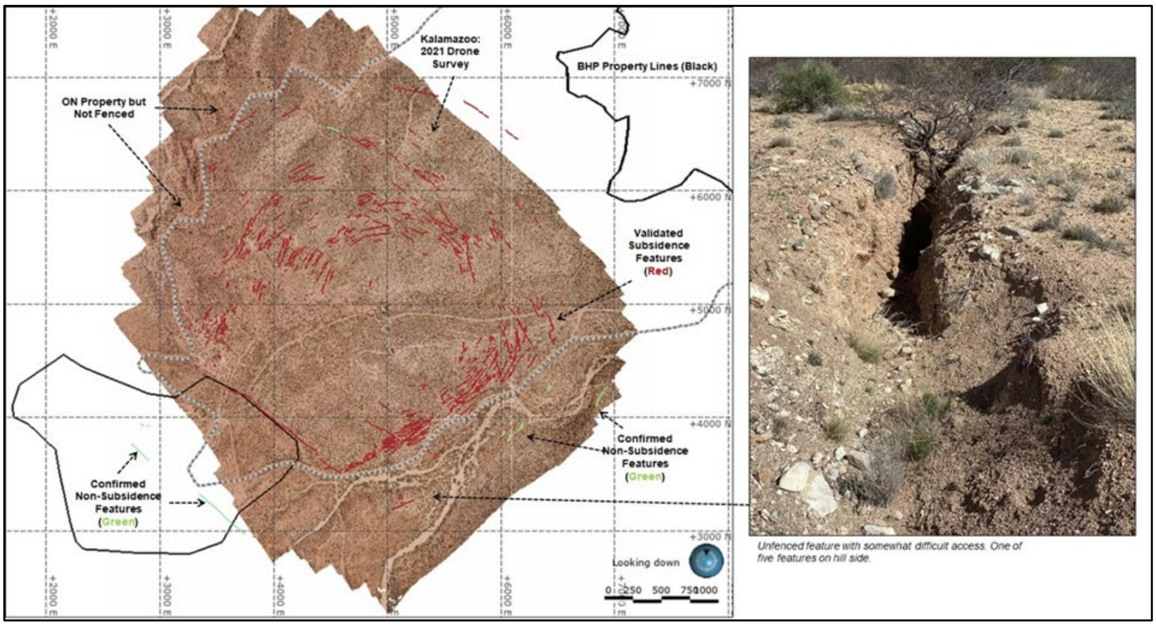

Figure 8 Periphery crack mapping at Kalamazoo including features verified as non-subsidence

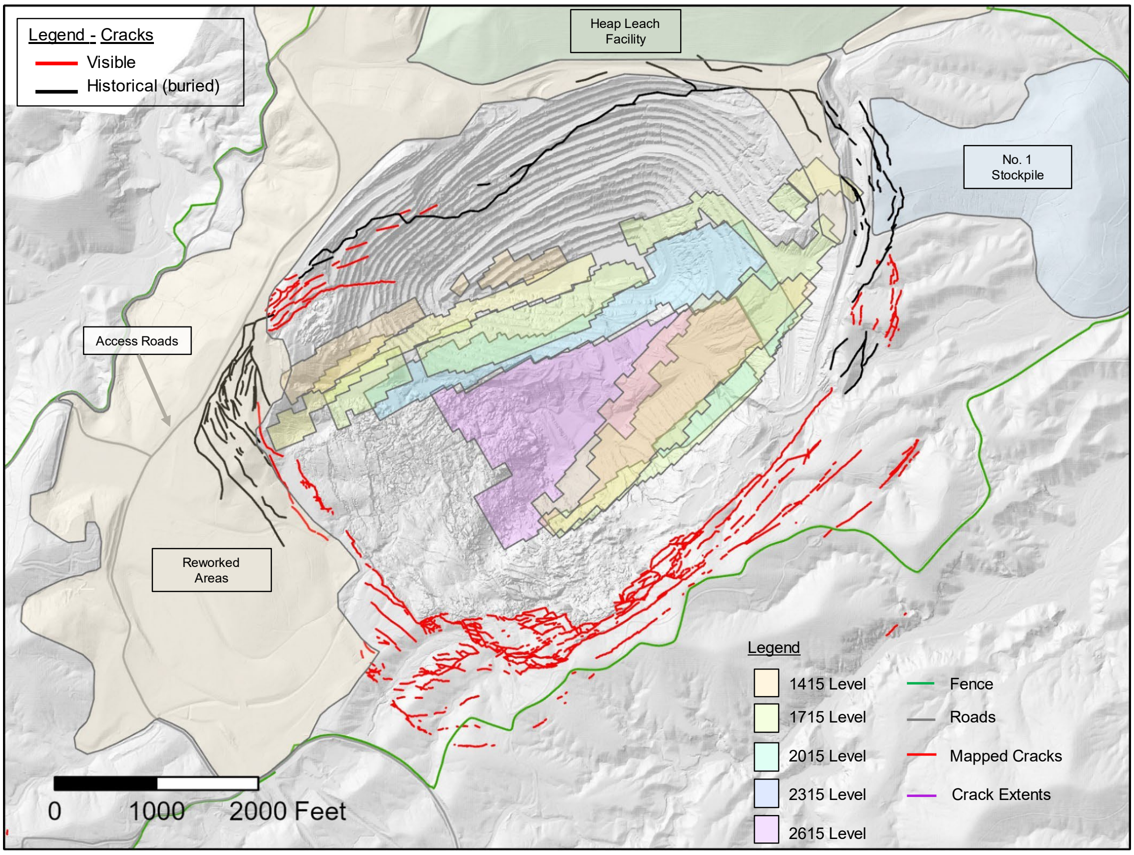

Figure 9 Periphery crack mapping at San Manuel showing visible and historical buried cracks relative to the underground cave footprints and site infrastructure

4.4 InSAR recent archive surveys

InSAR collects ground deformation using radar images collected by orbiting satellites from different vantage points (i.e., ascending and/or descending orbits). Recent archive surveys for San Manuel and Kalamazoo were completed by two service providers. The InSAR vertical displacement data highlighted areas that have exhibited noticeable displacement, mainly within the San Manuel subsidence crater, where materials have mobilized toward the open pit, in-pit rock dumps and former landfills.

Recent monitoring data were combined by overlaying aerial photos with digitized InSAR data and crack mapping using Global Mapper to interrogate the movement of specific tension cracks. An example showing the comparison is shown in Figure 10. Learnings from the InSAR investigations include:

- InSAR is appropriate for detecting medium to large scale movements, however, is difficult to detect small scale measurement in the continuous-subsidence zone. Horizontal and vertical displacement resolutions can be too low to accurately measure differential movement over some major cracks.
- The density of InSAR data points may vary due to vegetation, seasonal, or rapid surface changes or overall poor line of sight orientation relative to the topography.
- Sentinel and TerraSAR-X satellites produced a range of measurement accuracy. It is well known that the Sentinel is a low resolution (low cost) dataset, however, it can produce misleading trends when compared to the TerraSAR-X. Based on its higher resolution and ability to perform repeatable surveys, measurements from TerraSAR-X was used as the primary dataset.
- Movement was detected within the subsidence crater. These movements were above the noise threshold and agreed with field observations. The noise threshold was data with less than 5 mm per year. Detected displacements away from the crater were within the noise threshold.
- The short time frame of the available InSAR data limited the ability to determine longer-term trends.

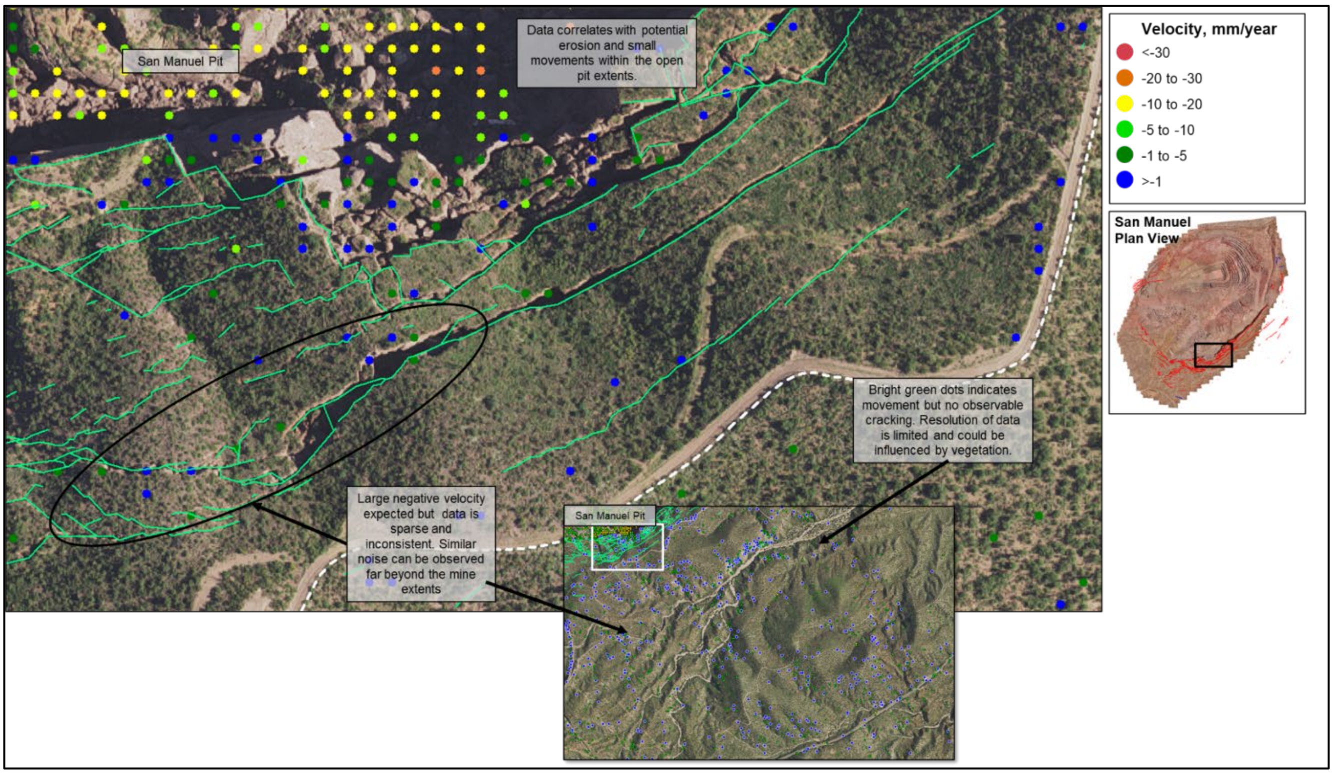

Figure 10 Focused comparison of InSAR datapoints and crack mapping (SRK 2023)

5 Comparison to empirical methods

The surface monitoring data findings were compared with Laubscher's subsidence extent estimate (2017) and Hatheway's 1966 site-specific periphery cave growth prediction tools.

5.1 Laubscher's method

Mining Rock Mass Rating (MRMR) values derived from historical geotechnical studies and verified with core review was used in Laubscher's break-back estimates for fracture and continuous-subsidence zone extents (Figure 2). The empirical estimates for San Manuel were accurate to the mapped cracking (within several degrees). The Kalamazoo estimates were less accurate in the southwest directions, as the crown pillar is still relatively intact with partial cave development. The estimate for Kalamazoo is shown Figure 11.

Limitations to the empirical approach are described by Contreras (2022):

- A inadequate understanding of the adjustment factors for MRMR, weathering, joint orientation, blasting, stress, water) may lead to inaccurate estimates and misuse.
- Structural influences due to discontinuities or faults are not considered. These features can either extend or shorten the overall subsidence zone of influence.
- Cave production rates and sequence is not considered. High rates of production can lead to hang ups or sudden landslides that may alter the influence of subsidence.

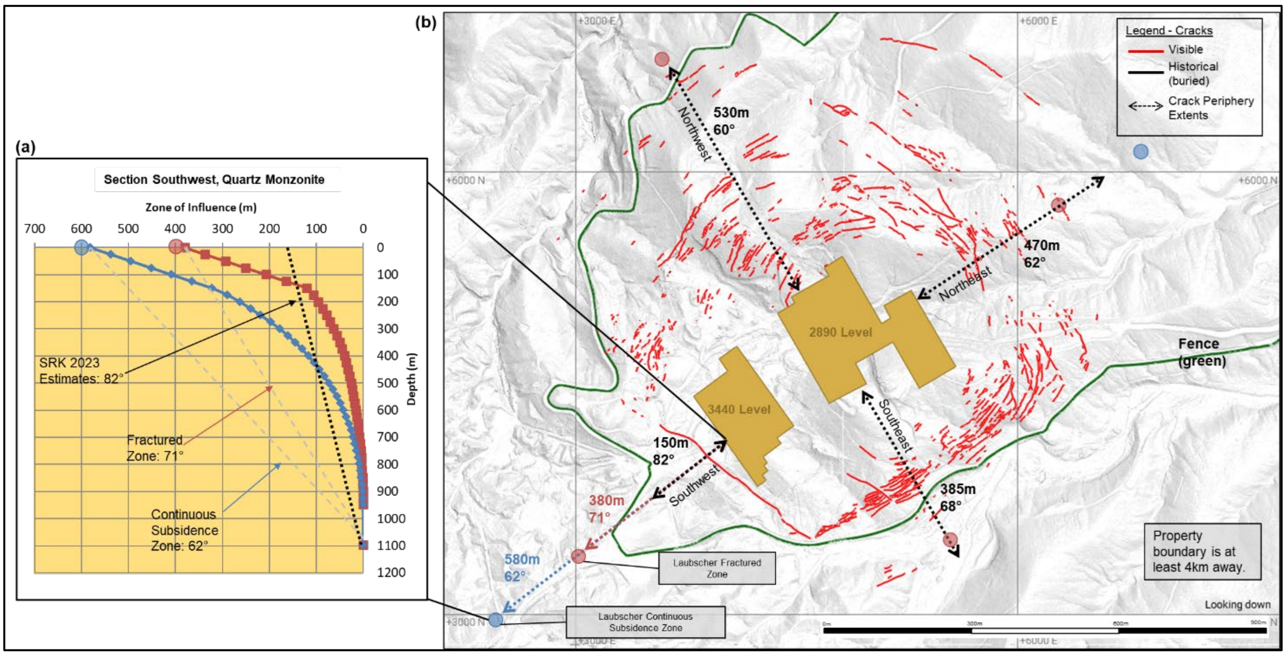

Figure 11 **Empirical estimates of subsidence extents at Kalamazoo compared with mapped periphery extents (black dotted arrow): (a) Graphical interpretations of empirical estimates southwest of the cave and (b) plan view empirical estimates in northwest, northeast, southeast and southwest direction**

5.2 Hatheway's subsidence periphery growth

Efforts have been made by Hatheway (1966) to record and qualitatively analyse the subsidence periphery growth of San Manuel as shown in Figure 12.a. . Although driven by production rates and mining sequence, the plot of peripheral growth can provide insight into the subsidence behaviour through time. Using aerial images from 1979 to 2022, peripheral lengths of San Manual and Kalamazoo were estimated and plotted with data from Hatheway (1956 to 1965), as seen in Figure 12b. While there's an exponential displacement rate during production, a flattening curve is likely to be observed during the post-caving period.

Limitations to this empirical approach includes:

- The estimation is purely qualitative and does not consider rock mass properties, structural control, cave footprint and geometry, material density and other adjustment factors.
- Although a general trend can be interpretated, the rate of subsidence through the flattening time-period is difficult to quantify unless a more accurate monitoring methods are applied (e.g., extensometers, prisms on specific features).
- The accuracy of new peripheral measurements is limited to the aerial imagery resolution and visual observations, as discussed previously for the USGS aerial imagery catalog.

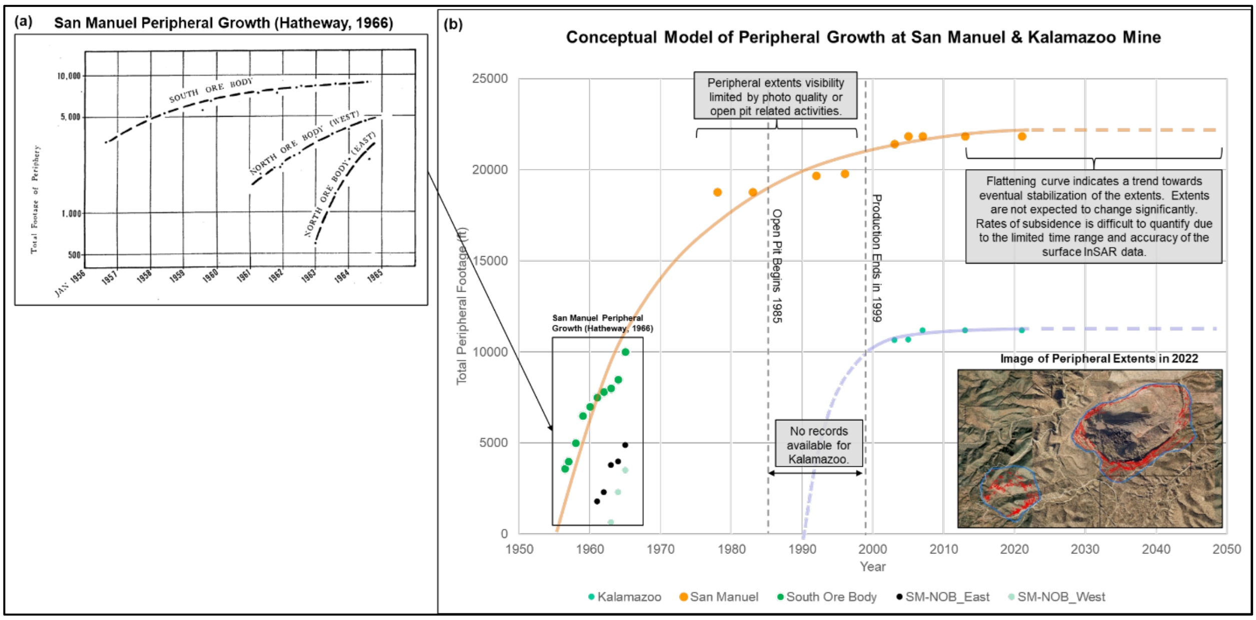

Figure 12 **(a) Conceptual model of peripheral growth based on Hatheway (1966), (b) interpreted peripheral growth at San Manuel & Kalamazoo Mine based on peripheral extent measurements from 1979 to 2022 (right).**

6 Conclusions

This paper presents an examination of the monitoring dataset used to evaluate the post-caving subsidence at the San Manuel and Kalamazoo mines. Although conclusive findings from each applied monitoring technique can be determined, it is difficult to correlate between methods due to contrasts in resolution and gaps to the available historical record. Several concluding comments with respect to the monitoring resolution are provided:

- Crack mapping is necessary for continuous monitoring with focused areas based on aerial photo interpretations.
- InSAR monitoring is appropriate for detecting large movements in the fractured zone provided they are in line with the satellite's line of sight. However, higher resolution monitoring technique should be used to determine small scale displacements in the continuous-subsidence zone.
- Aerial photography is helpful in providing 2D historical context to changes in topography, but this method is purely qualitative and difficult to quantify and determine future subsidence extents.
- Laubscher's empirical method is appropriate for a first-order estimation for the extents of subsidence, however, the influence of input parameters including geological model, adjustment factors and structural influences should be well understood. This comment is appliable to complex numerical methods also.
- Based on establishing an up-to-date baseline, techniques such as survey pins and extensometers form a part of the future subsidence monitoring activities that could be used to verify the study findings.

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