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Videoscope Applications to Interpret Lithology in Underground Coal Mines

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ABSTRACT

The understanding of coal mine roof lithology is a critical component in the determination of engineering solutions for roof control. Coreholes were the first technology available to determine lithology of the roof in reserve areas, but coreholes are typically drilled 500–2,500 ft apart due to their cost and sometimes reach more than $125,000 dollars per hole, depending on mine conditions. The next method developed to bridge this gap was the fiber-optic scope which is utilized in the roof at the faces of underground development. High-end fiber-optic scopes can also be costly (20,000–40,000 dollars) but are more affordable than drilling a corehole, and the information can be processed immediately to make quick roof support determinations. The fiberscope can be operated wherever a roof bolter can drill a hole, and there are no restrictions related to property owners, proximity to streams, elevation changes, etc. The latest borescoping method utilized by mining companies is the use of videoscopes. Videoscopes and all borescopes in general are limited by the lengths of the scope and the length of the borehole drilled in the mine. Videoscopes have the advantage of being able to record video while examining the roof lithology. The information can be recorded quickly underground and then be examined on the surface which allows anyone to capture the video so that a geologist can make lithology descriptions without ever going underground. In the past, videoscopes had limited resolution, a short battery life, were fragile and were relatively costly. As technology progresses, videoscopes have become more affordable, have increased battery life, and offer enhanced 1080p resolution. With the broader availability of affordable videoscopes, videoscopes can be more readily used in various mine environments at every active section underground. This paper will discuss the types of videoscopes available, the features that will aid in lithology description/identification, the deployment methods pertaining to supplemental roof support recommendations, and an advanced methodology to enhance accuracy in understanding roof lithology.

INTRODUCTION

The ability to identify the roof lithology in a mine entry is essential in designing effective ground control systems. Corehole drilling is costly depending on the drilling depth and types of strata encountered. The expense of drilling a corehole can be more than 100,000 dollars per hole and coreholes provide sparse data points because they are typically drilled 500–2,500 ft apart. With the invention of various borescope technologies ranging from the early ridged periscopes to today's high definition videoscopes, the ability to discern roof lithology has become more accessible than ever. This paper will discuss the types and features available on modern videoscopes and will present methodology to produce video stratigraphic columns of recorded images by performing additional processing of images produced from all videoscopes.

BACKGROUND

Borescopes were first introduced with rigid sections that would require assembly and with a large incandescent light source and prism. The entire assembly was bulky and required more than one operator. The roof hole drilled for observation was required to be larger than the normal 1-inch diameter hole needed for most types of roof bolts, which needed a specialized drill bit (Fitz Simmons, 1979). These borescopes did not meet the intrinsic safety criteria required to obtain Mine Safety and Health Administration (MSHA) approval for use inby the last open crosscut of a development section. Because of that restriction, borescopes could not be used to identify roof lithology at the face of an active mining section.

The first fiberoptic borescope was developed in 1979 by the U.S. Bureau of Mines. The fiberscope was 6-ft long and light enough to be operated by one person. The light source for the scope utilized an MSHA-approved miner's cap light which was permissible inby the last open crosscut of a development section. The scope also included a camera to take still images of the strata in the roof (Fitz Simmons 1979).

Many papers have been written discussing the benefits and deployment strategies of borescopes. This section will discuss some of the key advancements utilizing borescopes, since its inception, to identify roof lithology for roof control. James Tennant showed the practicality of borehole scoping by describing the use and analysis of fiberscope observations. The analysis included geologic cross sections developed directly from the data collected from a borescope that displayed changes in roof lithology through 4 entries at Martinka No.1 Mine. The borescope observations highlighted mud seams in the roof that caused support issues which resulted in the mine changing to longer primary bolts to achieve anchorage above the mud seams (Tennant, James M. 1982).

John Shepherd utilized the deployment of borescopes to identify roof lithology and roof stability throughout longwall gateroads. He concluded that borescopes are a beneficial tool to identify lithological variations and roof fractures. Identifying the changes in lithology and mapping the features aids in determining roof support decisions (Shepherd, J. et al. 1986).

Borescope usage has also led to roof control improvements in other underground mining commodities such as limestone. John Ellenberger developed a numeric rating system for roof conditions in stone mines called the Roof Quality Index (RQI). The RQI rating is based on borescope observations and provides a numeric value to the observed roof lithology based on partings, cracks, stylolites, and lithologic changes. The system improved on the understanding of roof control and its stability (Ellenberger, J. 2009).

Considerations to deploy borescopes for entry stability, identify geologic hazards, and project hazards into future reserves was developed in a paper by Mark Van Dyke et al. (2019). The paper highlights how to collect geologic data from borescopes, how to use borescopes to determine supplemental roof support, key features to look for while collecting information underground, and additional borescope uses such as examining inside a pillar or the floor. A case study, also discussed in the paper, proposes how the use of borescope technologies can be applied to identify a geologic transition zone from sandstone to limestone (Van Dyke et al. 2019).

BORESCOPES OF TODAY

Fiberscopes (see Figure 1) are still in use today and are remain the only practical option for permissible borescopes in the United States. However, a popular and cost-effective option to examine mine roof lithology is to utilize a video borescope. Video borescopes have the advantage of recording the image from the entire borehole to allow replay of the video on a computer. Until recently, fiberoptic borescopes were favored when examining roof lithology because of the limitation of video borescopes recording in 480p resolution. This is not optimal for lithology identification. Typically, the limit of optical clarity of a fiberscope is dependent on the user's vision and the brightness of the light source being used. Fiberoptic borescopes remain relatively costly, typically costing in the tens of thousands of dollars, so their use is often limited to larger mining operations.

Videoscopes have become more prevalent as the technology improves and market prices drop. Their popularity increased when videoscopes began to offer 1080p recording resolution. This helped to bridge the gap of the advantage of the resolution of fiberscopes with the videoscopes' ability to record and keep a digital file. The higher resolution of today's videoscopes have all but made fiberoptic scopes

Figure 1. Fiberscope with a miner's cap light

obsolete, except for operating inby the last open crosscut. Because of the improvements and increased availability of modern video borescopes, they have quickly become the most widely used borescope for mine roof lithology identification in the United States.

Videoscope prices range widely based on features, resolution, and manufacturer. The top tier videoscopes can cost multiple tens of thousands of dollars, and provide features such as removable batteries, faster processors, better screen refresh rates, removable head prisms (for different viewing angles), and have larger viewing screens. In addition to the features, the materials used to manufacture them are of better quality such as stainless-steel jacketed wires, quartz prism head windows, and rotating head windows. These types of videoscopes are less commonly used mostly due to their cost, and most mines have instead turned to lower cost videoscope alternatives.

VIDEOSCOPE FEATURES

When selecting a low-cost (under 300 dollars) videoscope for mining applications such as lithology identification, there are certain features, as described below, that will enhance the overall experience and accuracy for the end user. While some of these features may not be available in the low-cost models, opting to have them at a potentially increased cost may offer the end user a package tailored for their specific needs.

- Adjustable LED light intensity – Proper lighting, when viewing the borescope image, is extremely important. Too bright of an intensity can cause an overexposure that may whiteout the video screen. This is especially the case when water is in the borehole causing reflectance. Also, a low light intensity may result in loss of critical details necessary to classify roof lithology. An adjustable light will aid in controlling the amount of reflectance to avoid over and under exposure.
- Microphone –The ability to record sound will help with analyzing the data collected as the ability to replay the lithology interpretation as it is being called and the depths at each interval as they are occurring adds value to the video. It should be noted that it is a good practice to maintain a field notebook while interpreting the lithology and depths at each change in case an audio recording feature is not available, the sound level is too low, or background noise is too high to hear during video playback. The microphone works best when located on the video screen unit and not on the camera head.
- Length – The length of the borescope wire between the video screen and the top of the camera window required will depend on the length of the longest roof bolts the mine uses for support. The length of the roof bolts is dependent on many factors such as lithology, geologic structures, and overburden. A videoscope with the length of approximately 20 feet should be sufficient for almost every coal mine in the United States based on the maximum length of supplemental cable bolts observed in field data collection visits. Some video borescopes can come in 50 ft or longer and should be carefully considered. The additional wire length can be cumbersome and affect portability, especially in dark underground environments and other confined spaces.
- On-screen depth indicator – An on-screen depth indicator is another feature that is very helpful when examining lithology during video playback. If depth is not displayed on the video, simple depth indicators can be applied onto the poles used to insert the videoscope into the roof borehole. As previously discussed in the microphone section, it is recommended to keep a physical log to backup any video taken.
- Multiple cameras – Dual camera systems are typically configured in a forward (vertical) and right-angle (side) view to catch both the borehole in a 360-degree and 90-degree bedding view. Some older models will only have a vertical camera with a magnetic mirror to see at 90 degrees. The magnetic mirror can detach and be easily lost during operation and is not recommended. Some of the newer models of video borescopes have a triple lens configuration which includes a macro camera for clear images very close to the rock within a borehole.
- Secure Digital (SD) card – Most video borescopes utilize SD cards as the medium to store data. SD cards can vary from storage capacity and writing speeds. When recording video (and especially if the borescope has a microphone) ensure that the SD card storage size is adequate. Typically, recording video will utilize a 16-GB SD card at the minimum. Depending on resolution settings, audio/video capabilities, and duration of data collection, operators (operators vs operation/use of the unit) may require a higher storage capacity.
- 1080 Progressive Scan recording – High definition (HD) images are necessary to be able to see lithology clearly for accurate identification. In HD, small features can be seen such as sandstone grain size, mica streaks, thin beds of coal, and micro cracks.

Identifying these features is critical to understand the rock mass in the roof and how it will respond to various types of support designs. Videoscope users should be aware that some systems will record in 1080p, but often the video screens on low cost videoscopes are only capable of displaying in 720p resolution. Playing the video file back on a PC, that has a 1080p monitor, is the best method to review the image in the highest resolution possible. 4K resolution videoscopes are becoming increasingly available at lower costs, but the higher resolution creates larger files to store on a computer or SD card.

- Processor and screen refresh rate – Processor speed and screen refresh rate information is not typically advertised for most models. A slower processor speed and screen refresh rate can make the video feed choppy or jumpy which makes real-time identification of lithology difficult. The images are best viewed when the screen refresh rate is higher than 20 frames per second (FPS). Determining processor speed can be very difficult since many of the video borescope companies do not use the same nomenclature as computers. If the refresh rate is low, the user should slow down the speed at which the camera is moving throughout the hole. Refresh rate makes a significant difference with the clarity of video playback. For example, the image clarity produced by a video borescope moving down a 1-inch borehole in shale, may vary widely depending on the speed of travel. (see Figure 2)
- Screen size – The larger the screens on the video borescope, the easier time the user will have identifying the lithology in real-time. A screen size of 4 inches or larger should be considered for most mine roof borescoping tasks.
- Lens focal point – The focal point of the borescope lens is critical to have a clear image of the borehole. Most current models have a focal point that starts at 1.2 inches which will cause images to be out of focus in a standard one-inch diameter roof borehole (see Figure 3). In Figure 3, three different borescopes were used to demonstrate how important lens focal point can be when determining lithology. In figure A, the focal point is 1.2 inches in a 1-inch diameter borehole from a lower-cost videoscope which creates a blurry image of sandstone. In photo B, an image from a lower-cost videoscope of broken sandstone is viewed with a lens focal point of 0.59 inches and the image is much clearer than photo A. The photo of C is of laminated sandstone and shale viewed from a higher-cost borescope with a focal length of 0.50 inches. A video borescope lens focal point of less than 1 inch will help provide the best image possible. Even with the proper focal length, utilizing a spacer with the borescope lens will greatly enhance the final video by providing an equal focus distance throughout the entire borehole video.

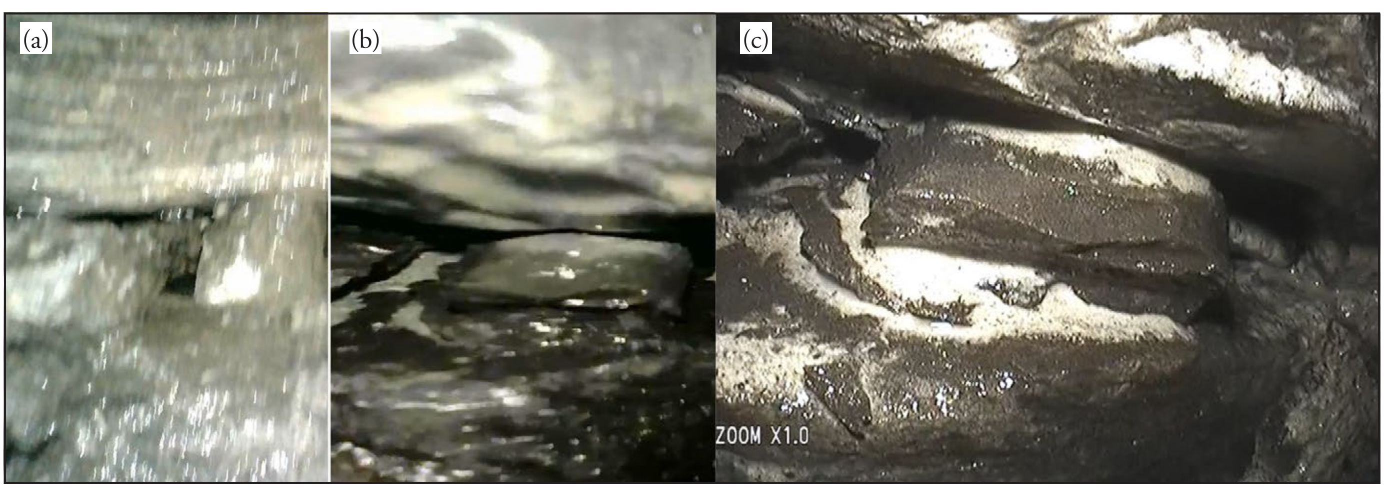

Figure 2. Screen refresh rate viewing the same crack moving down the borehole at the same rate of speed: (A) is the image of a crack with a low-cost videoscope with low refresh rate; (B) is the image of a crack with a low-cost videoscope with higher refresh rate; (C) is the image of a crack with a high-cost videoscope with the highest refresh rate of the three videoscopes.

IMPLEMENTATION OF VIDEO BORESCOPES AT MINING OPERATIONS

The video produced at one borehole underground can provide very specific information about the roof rockmass in one location. Some features that can be seen are cracks in the strata, horizontal shifts, changes in lithology, observing glue migration, methane, slicks, and changes in bedding thickness (see Figure 4). During the observations, notes should be taken to describe the type of lithology, the thickness of bedding planes, any inclusions (coal streaks, sandstone or shale streaks, clay, etc.), and the overall thickness of the rock unit. These descriptions will assist geomechanical engineers in understanding the strength of the rockmass in the roof of the mine and implement better support plans to reduce roof falls.

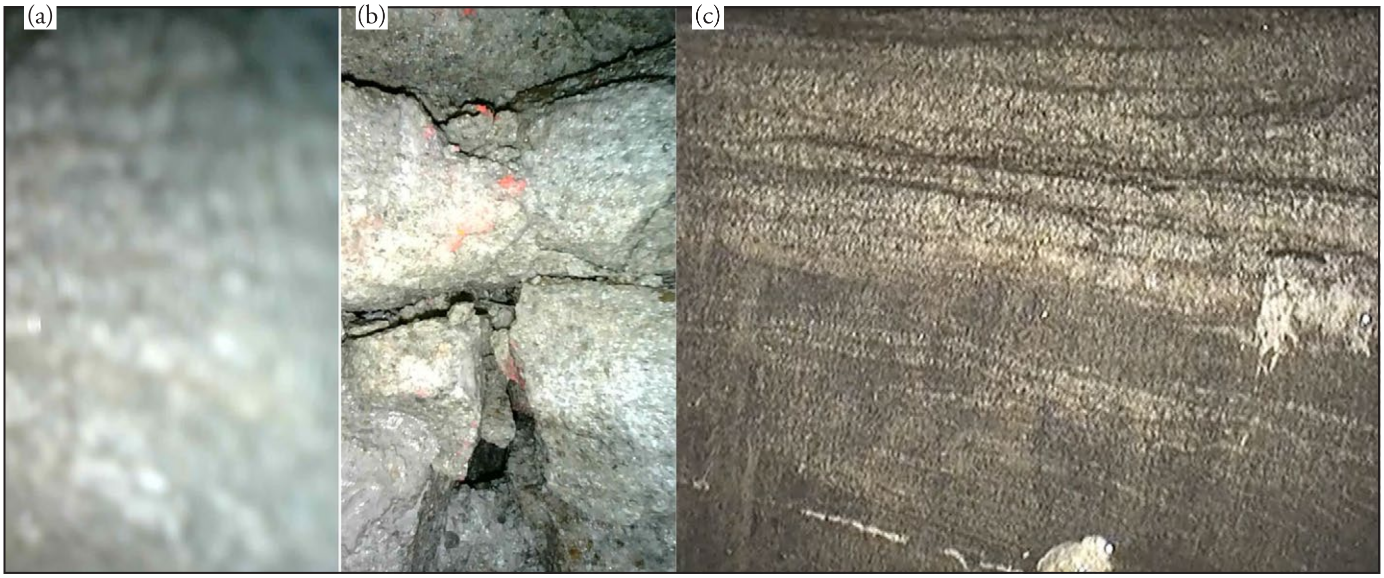

Figure 3. Three images from video borescopes in a 1-inch diameter hole: (A) is a picture of sandstone from a lower-cost borescope with a focal point of 1.2 inches; (B) is a picture of broken sandstone from a lower-cost borescope with a focal point less than an inch; (C) is a picture of a contact between sandstone and shale from a higher-cost borescope with a focal point of less than one inch.

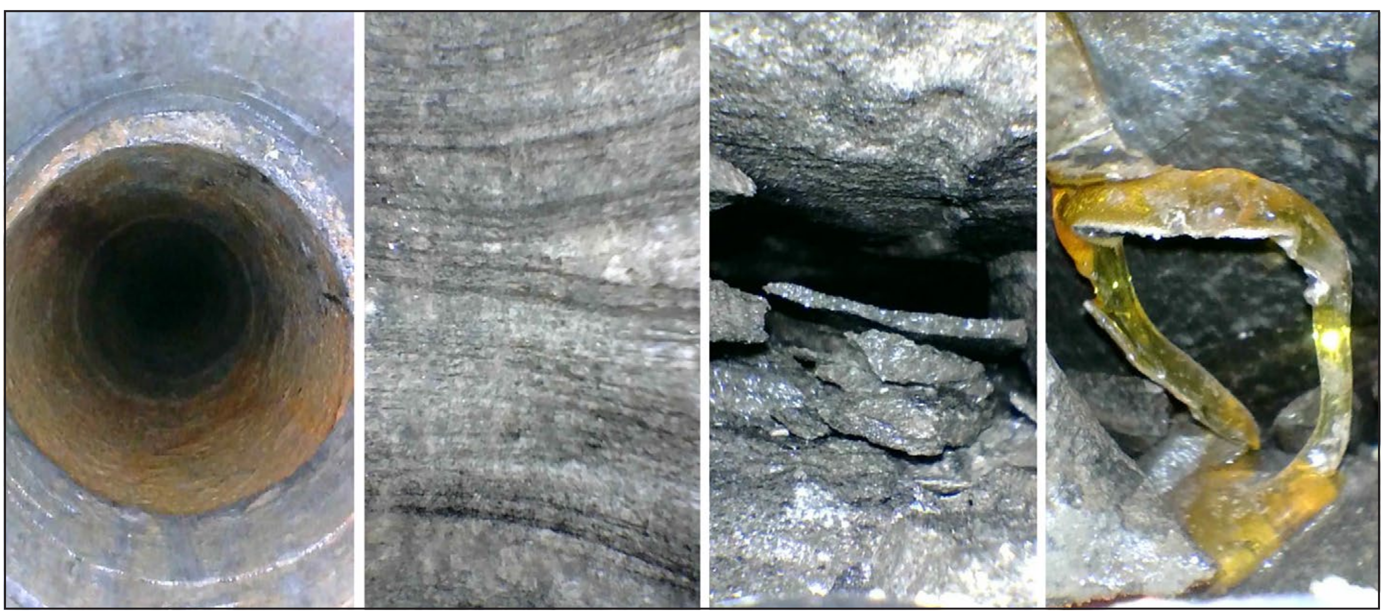

Figure 4. Videoscope images of (from the left) a horizontal shift, laminated strata, crack in sandstone, and glue migration. All of these images were taken with a low-cost videoscope

The lithology information from the video borescopes is best understood in relation to the roof stability in a gateroad or section by creating a geologic cross section from the data. If a more global view is needed, then a geologic model will be more appropriate. Regardless of a cross section or geologic model, the purpose of the data must be clearly seen and easily interpreted by engineers. In using the creation of cross sections, the roof should have bolting horizons so that engineers know if they will decide to use a certain bolt length and the type of lithology that bolt will be anchored into (see Figure 5). If a geologic model is needed (see Figure 6), color scheme is very important to quickly understanding the map or image. Generally, it's best to use cooler colors (blues and greens) for good conditions and hotter colors (yellow, orange, and red) for bad conditions. This will help mine management quickly identify the locations that need attention and help direct roof control efforts to where they are needed.

VIDEOSCOPE IMAGE STITCHING

Borehole video stitching can be a valuable technique for visualizing geological features in a borehole. By stitching together multiple video frames, a stitched view of the borehole can be created, allowing for a comprehensive visualization of the geological formations and structures.

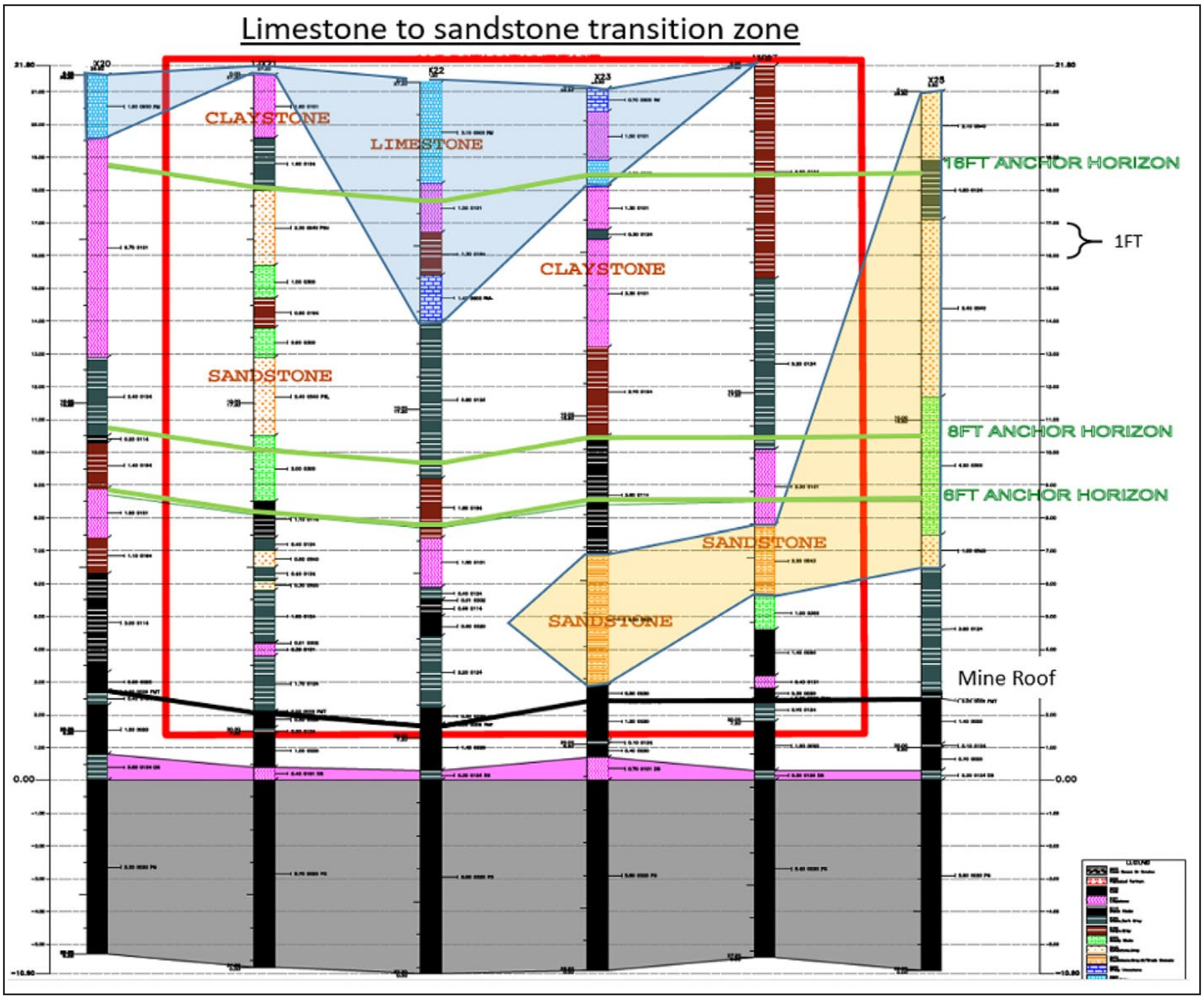

Figure 5. Geological cross-section generated from images from a borescope capturing a limestone (in blue) to sandstone (in yellow) transition with bolting anchorage horizons added (Van Dyke et al. 2015).

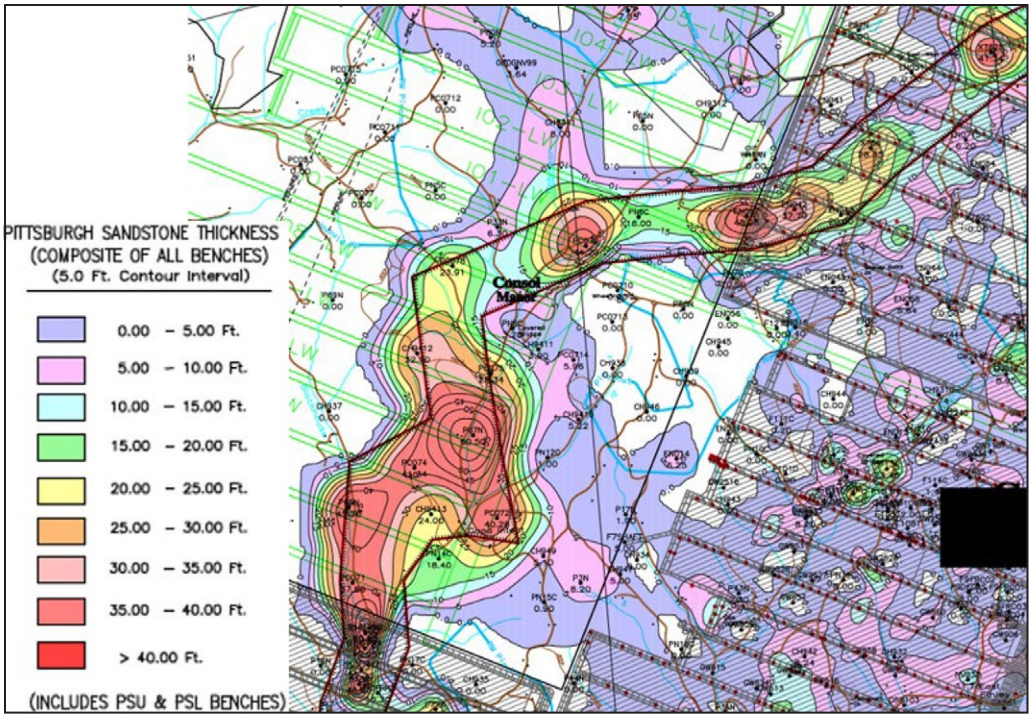

Figure 6. A geological model highlighting the Pittsburgh Sandstone thickness. The red areas indicate thickness over 40 feet which could cause longwall caving issues for the mine.

The general process for image stitching with a borehole video includes image acquisition, feature detection and extraction, feature matching and filtering, transformation estimation, image warping, and image blending.

1. Image acquisition is the process of capturing a set of overlapping frames from a video for stitching. Two images are captured from a borehole video (see Figure 7) for the following demonstration.
2. The process of feature detection and extraction uses a feature detection algorithm, e.g., Scale-Invariant Feature Transform (SIFT), Speeded-Up Robust Features (SURF), Oriented FAST and Rotated BRIEF (ORB), to identify distinctive key points in each image and extracts the descriptors associated with these key points, which capture the local image information. The types of key points can be detected depending on the algorithm and method used for key point detection, and the common key points include corners, blob-like structures, edges, maxima, or minima. The key points that were detected were with the ORB algorithm (see Figure 8).
3. The key points and descriptors between pairs of images are matched to establish correspondences in the feature matching step. The purpose is to find matching key points between the images based on their descriptors. However, a key point in one image may have multiple potential matches in another one based on the descriptors (see Figure 9). The filtering step potentially filters incorrect or ambiguous matches. Figure 10 shows the matched features after filtering, and we can see that, after filtering, the overall accuracy of the feature matching processing is significantly improved.
4. In the transformation estimation step, the transformation (scaling, rotation, and shift) between each pair of images is estimated to find the geometric relationship between the images so that the images can be aligned properly.
5. Based on the estimated transformation, the images can be warped. It involves applying the calculated transformation matrix to each image to align them and create the stitched image.
6. The warped images can then be blended to create a seamless transition between the overlapping regions. The purpose is to ensure the visual consistency of the stitched images without noticeable seams. The image blending step is still under development and is not used in this paper.

A series of frames can be captured from a borehole video. For each of the two adjacent frames, the key points can be detected, matched, and filtered, and the transformation

Figure 7. The original images for stitching

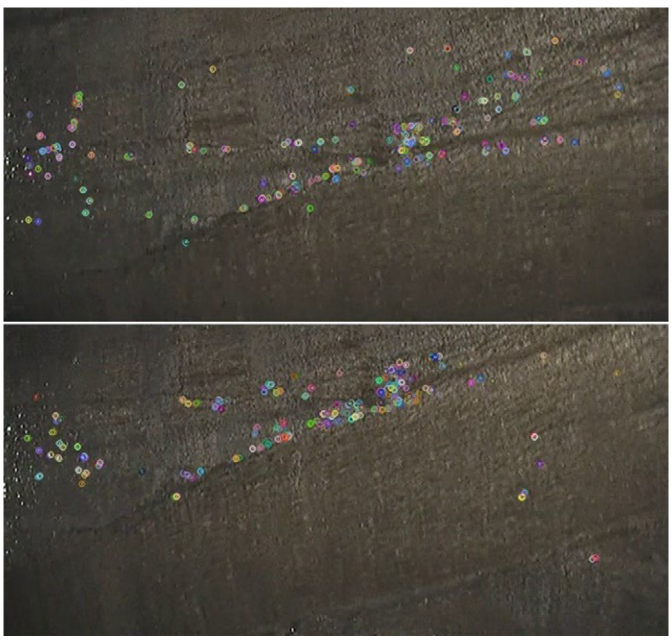

Figure 8. Key points that were detected with the ORB algorithm

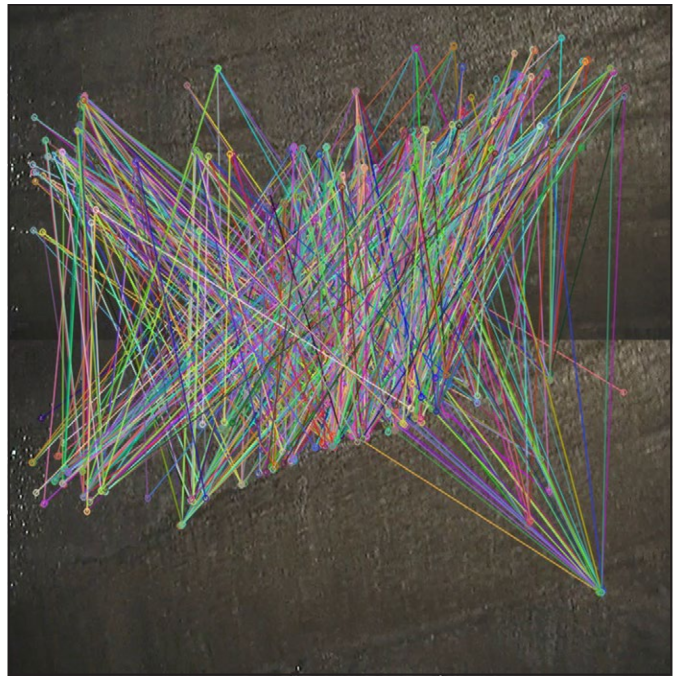

Figure 9. All matches of key points that were detected.

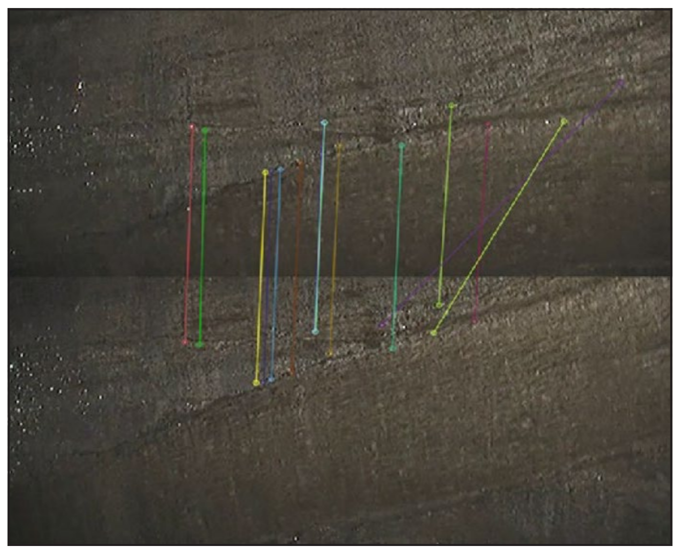

Figure 10. Filtered matches of key points between two images

matrix can be calculated to align the current image to the previous one. Starting from the first one, the frames can be aligned and stitched one by one to get the stitched image of a borehole. One segment of a stitched borehole image is shown (see Figure 11). It can be found that, even without blending, the geological features can be easily identified in the stitched image. Researchers at the National Institute for Occupational Safety and Health (NIOSH) are working on improved methodologies involving the stitching of borescope images to ultimately have a vertical image without the offset (see Figure 11). After image straightening, a measurement scale can be applied to the image so that the images could be directly used in a geological cross section.

Figure 11. Multiple images stitched together from a continuous section of a borehole

CONCLUSION

The features and resolution of video borescopes brings new opportunities to enhance mine workers' safety and health. Their applications enable mine workers and safety professionals to quickly examine roof conditions and observe for cracks or other features. The video can be recorded and downloaded to a network so that geologists can review the video and share the assessment of the rock mass in the roof with ground control engineers at a quicker pace than ever before.

Choosing the correct videoscope with the optimal features may be dictated by individual operations and budgets. However, considerations should be made related to the 8 features discussed within this paper such as a larger screen, correct focal length, and fast refresh rate. The ability to view a clear image of the borehole can make the difference between knowing how to best support the roof or making an educated guess. A quality 1080p video will capture the bedding planes, inclusions, lithology changes, and cracks that are present to understand the strength of the lithology in the roof.

Representations of the strata from the videoscope images can be displayed in geologic cross sections, models, or images stitched together to give geologists and geomechanical engineers the best visualization possible of the rockmass. This will aid in quicker and more informed decisions from mine geologists and engineers to implement sound roof control practices.

LIMITITATIONS

The features discussed and images captured were from four videoscopes that NIOSH researchers had access to and have used in data collection at operating mines. Accordingly, there may be other products and features that may produce different results in analyzing videoscope images. Videoscope images may vary between models, and the comparisons between the four videoscopes is a limited sample of what is available in the marketplace.

DISCLAIMER

The findings and conclusions in this report are those of the author(s) and do not necessarily represent the official position of the National Institute for Occupational Safety and Health (NIOSH), Centers for Disease Control and Prevention (CDC). Mention of any company or product does not constitute endorsement by NIOSH.

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