Photogrammetric Discontinuity Mapping as Applied to Structural Interpretation and Drillhole Planning at Barrick’s Williams Pit

J. I. Mathis  Zostrich Geotechnical, Ellensburg, USA

Abstract

This article describes the photogrammetric characterization of Barrick Gold's Hemlo operations, Williams open pit slopes, the subsequent data reduction, structure interpretation, and incorporation of the data in geotechnical drillhole planning.

Due to access constraints, it would be challenging to physically detail map the presently exposed pit walls. Climatic constraints preclude mapping during the winter months when snow covers the benches. Structural mapping using photogrammetry allowed for completing coverage of the entire pit in roughly three days.

The near complete aerial coverage of essentially the exposed pit walls coupled with detailed discontinuity mapping provided not only characterization of major structural zones, including structural domain variations, but allowed minor nuances in fabric structural orientation to be determined. As these minor changes in fabric orientation can have a substantial impact on bench face design, they are of import from a geotechnical perspective.

The structural characterization described in this paper was also utilized to plan/locate geotechnical drillholes for potential pit expansion. This drillhole planning incorporated drillhole intersections of potentially adverse structures and fabric by geologic domain as well as major structure extensions from the photogrammetric pit wall mapping. Given the detailed characterization, drillhole orientations could also be selected such as to minimize drillhole orientation bias effects on the structural data obtained from the drill core as well as minimize impact of pervasive sets on core integrity.

Benefits of the detailed pit mapping are that the resulting structural models for fabric and major structure include a significant reduction in total required drilling, an associated reduction in drilling cost, and a robust and reliable structural model. The latter should, if properly incorporated into design, result in an optimized slope with associated lower risk of failure.

1 Introduction

A project to conduct and interpret, photogrammetric mapping of the Williams open pit at Barrick Gold’s Hemlo mine (Figure 1) was initiated in August 2010. Photogrammetric mapping was considered, not only for the detailed coverage provided, but due to site regulations that limited access to the bench faces restricting physical mapping. The project had multiple goals, among which were: the detailed photogrammetric structural mapping of the exposed pit walls, major structure interpretation of the photogrammetric structural data and evaluation of existing bench face angles coupled with comparison to theoretical bench face angles from analysis of the structural data.

This project then evolved into assistance with locating oriented geotechnical drillholes that were being planned in the pit walls. This assistance revolved around targeting interpreted major structure and potential parallel features. In addition it required the optimization of drillhole orientations such as to maximize core recovery while minimizing orientation bias for critical discontinuity sets.
2 General geologic setting

The Williams pit is situated in the Canadian shield in rocks that are generally Archean in age, being about 2800 to 2700 My. The north and south walls of the pit are composed primarily of metadsediments, the west wall is Moose Lake porphyry, and the east wall exposes a cross section through most lithologic units. Sub-vertical diabase dikes transect the pit in a north-south direction, and are obvious in the structures shown in Figure 3.

The protolithologies of the area, while potentially affecting the rheology of the units during deformation events, do not appear to have significantly affected major structure persistence or orientation. Fabric is, however, affected to a certain extent. This has not been addressed herein.

3 Site photogrammetry

The photogrammetry layout was pre-planned, to the extent possible, prior to the site visit. Subsequent to a brief site inspection, control points were placed (painted) on accessible benches such that they would be visible from the planned camera stations (Figure 2). Geologic and structural characteristic observations were annotated at the time of control point establishment in order to assist with later interpretation.

3.1 Equipment and layout

Photogrammetry was conducted with a Canon 5d Mk2 camera with a resolution of approximately 21Mp. All photogrammetry was conducted from a survey tripod, with the nodal center of the objective centered over the rotational center of the tribrach, and using a remote shutter release. Camera station locations are indicated on Figure 2.

For the images taken in excess of 400m (upper portion of north wall from south wall), east wall (800m), and west wall (800m), a 200mm objective was utilized. All other photogrammetry was conducted with a 135mm objective.

Photogrammetry of the pit walls for major structure interpretation as well as cell mapping required roughly 40 hours of field work. This includes placement of the control points.
3.2 DTM/photogrammetric model creation

Model creation was conducted using Adamtech Calibcam and 3DM Analyst (2.3.4 Build 743). A total of approximately 88 individual models, ranging from 200,000 to 1,200,000 reported DTM points each, were created for the major structure interpretation.

Model creation, including corrective re-creation due to program errors, required approximately 80 hours of work. This averages out to be slightly less than 1 hour per model. Much of this time was spent matching photographs due to multiple overlapping panels being taken, digitizing control points, and ensuring that the resulting DTM models overlapped properly to allow relatively seamless mapping.

3.3 Photogrammetric structure selection

Structures were selected from the aforementioned models using Adamtech’s 3DM Analyst. An approximate truncation level of about 0.5-1m was utilized for mapping, although this was somewhat variable depending on the quality of the model, rock exposure (broken rock covered some slopes) and distance from the camera to the target area.

A total of 8,438 structures were mapped (Figure 3). This required roughly 100 hours of digitizing.

Summary of the aforementioned time expended indicates that about 220 hours in total was spent in direct collection of the structural information, or about 40 structures per hour. Given that many of these structures were very continuous, and/or in inaccessible locations, and could not be collected using standard field mapping techniques, the data collection rate would appear acceptable. Further, this data was comprised of orientations derived from generally accurate representations of large scale features (as compared to handheld compass measurement), included location information to within centimetres, and included some measure of continuity, all of which are critical to detailed structural analysis.
4 Structural data analysis

Initially, the collected data was compiled for evaluation in a single polar plot (Figure 4). As can be seen, this appears to indicate a generally orthogonal structural system. It also confirmed the general structural situation as described by mine staff, and as generally described in other external geomechanics reports. However, as will be shown, there are many subtle structural differences hidden within this data that are simply masked by the global presentation of the data.

4.1 General structural comments

Foliation strikes generally east-west with a general dip to the north. The “foliation set” appears to be composed of two discontinuity sets with a separating dihedral angle of around 10-20°. This variation is pervasive with the two “foliation” discontinuities often seen crossing one another. It is difficult to discern two separate sets if a large aerial swath is taken. Local domain segregation is required to see/isolate distinct discontinuity sets.

Cross jointing is sub-vertical and strikes generally north-south and is again separated into two distinct sets.

Sub-horizontal cross jointing appears to have a slight dip to the south. It is very undulatory and discontinuous, yet strangely persistent in plane. As for the foliation and sub-vertical cross jointing, this too is composed of two distinctly oriented discontinuity sets.

Dikes, while generally following the cross foliation structure, appear to also follow both foliation sets, as well as create sills on the sub-horizontal features. Step emplacement appears to be the rule rather than the exception.

As noted previously, the structural situation is much more complex than appears from the general polar plot depicted in Figure 4. As noted above, the foliation appears to be composed of two distinct discontinuity sets. So too does the cross jointing. In fact, as can be seen in Figure 5, there appears to be somewhat of a rotation of these sets relative to one another. This is not the first time such a rotation has been observed in foliated structural environments. It has been noted in at least three other projects conducted recently by this author, with the two foliation sets generally overlapping, but being obviously distinct in photogrammetric models.

The discontinuity sets of potentially greatest import to stability analyses in some structural domains essentially disappear in the global contour plot of Figure 4. Yet, they are distinctive sets (6, 8 and 10) as can be seen in the general discontinuity set representation found in Figure 6.
Additionally, the discontinuity sets appear to globally rotate by structural domain. While difficult to see in Figure 7 due to the size reduction of the original drawing, the rotation of the discontinuity sets can be observed by examining the contour highs on the polar plots.

**4.2 Major structure interpretation**

Major structures, and structural zones, were identified from measurements obtained from photogrammetric mapping. Discontinuity sets were labelled in such a fashion as to have generally similar orientation characteristics on the individual domainal stereonets. These discontinuity set identifiers were then attached to the individual structure orientations. Discontinuities were then plotted, by discontinuity set, at their correct spatial location relative to the pit wall.

Figure 5. Apparent rotation of discontinuity sets (base images from Adamtech 3DM Analyst).

Figure 6. General discontinuity sets with mean vector and 90% confidence ellipses (Z-Fabric).
Figure 7. General structural domains depicting rotation of primary discontinuity sets (Z-Fabric and Vulcan).
As only a single discontinuity set was plotted spatially, zones of discontinuity alignment, together with an increase in structural density, could be, and were, observed and utilized to determine major structure location and orientation. The provided structural model is draft in nature. “Fine tuning” is required in order to adjust structural zones such that they better match the photogrammetric models as well as confirm their local existence. Drillhole information, together with underground mapping information, could also assist in optimizing the structural model. Such adjustments can account for local deviation in orientation, continuity, and changes in characteristics, all of which may be important to slope design and performance.

An example of the draft primary foliation parallel major structures, as depicted in plan and section, is provided as Figure 8.

The stereonet of interpreted major structures is provided as Figure 9. Compare with Figure 4 in order to see the change in structural density and potential impact on pit wall stability analyses.

5 Drillhole planning

Oriented geotechnical drillhole planning for the feasibility study field program was assisted by results of the photogrammetry exercise. The targets for the drilling were:

- specific interpreted major structure that could be of concern to slope stability and;
- areas that could incorporate such major features in potentially adverse orientations.

Of course, the planning also required that drillholes be:

- spatially situated such that the orientation blind zone would not improperly sample critical features and;
- oriented relative to the foliation such that relatively sound core could be collected in disturbed areas near fault zones.

The resulting field layout as finalized and implemented by Golder Associates is presented in plan as Figure 10. An example of the stereographic projection layout for hole optimization is provided as Figure 11.

In general, the orientation data recovered from the drilling program matched the photogrammetric mapping. An example of a general comparison can be seen in Figure 12. Note that a detailed comparison was not conducted by the author.

Figure 8. Level plan and section (red line on plan) of primary foliation. Brown is diabase dike. (Vulcan).
Additionally, while not specifically conducted in detail by the author, a quick visual check was conducted to determine if major structure interpreted from the pit wall photogrammetric mapping continued to depth. An example of such a comparison is provided as Figure 13.

6 Bench face evaluation

While photogrammetry is of considerable use for mapping geologic structure, assisting major structure interpretation, and providing assistance from the resulting database in other data collection ventures, it can also be utilized for evaluation of attained slope performance.

For example, fabric mapping was conducted in the Williams pit for determination of local bench face angle predictions. This was then utilized for theoretical evaluation of potential bench face angles (Mathis 2002, 2007). These theoretical values were then compared to the field attained values in order to ascertain potential areas for face performance improvement as well as to evaluate potential model errors.
An example of a local bench selected for examination, as depicted in the Adamtech derived photogrammetric models is presented as Figure 14. These images indicate the evidence of scaling, sub-grade damage and the excellent performance of the face as demonstrated by the pre-shear half-casts, all from a variety of angles.

Figure 12. Comparison of domainal photogrammetric stereonet with local oriented drillhole (Z-Fabric).

Figure 13. Structural interpretation/confirmation using intercept orientations (Z-Fabric and Vulcan).
As can be seen in Figure 15, there are few potential wedge scale geometries that are dictated by local discontinuities. Further, the plane shear features are relatively shallow dipping. On the bench scale, local roughness and low normal stresses generally result in an increase in the apparent friction angle, especially if a curvilinear model, instead of a linear Mohr-Coulomb model, is utilized for strength distributions.

The resulting theoretical comparison for this specific area is shown as Figure 16. Note that the attained bench face angle has been collected from an area of the pit, not specific "profiles" through the bench (Mathis 2007). This provides a much better comparison with theoretical predictions as the bench population is incorporated in the comparison, not individual areas.

In the noted fashion, one can compare the actual attained bench performance with that predicted. Furthermore, any reasons for the attained bench face angles not corresponding with the predicted can be evaluated. This allows one to assess blast and/or scaling damage from a safe distance, utilizing perspectives not normally attainable in the field, all by using the photogrammetric models. Conversely, one can also determine if the model parameters, especially discontinuity persistence and density, appear to be adequately representing the area.
7 Conclusions

Detailed photogrammetric mapping can provide considerable benefit to any pit slope evaluation. It is, compared to other methods, a relatively inexpensive method to rapidly collect quality structural information from existing pit walls. This complete coverage allows for detailed structural interpretation including local adjustment for structural bends/rolls and local offset. The spatial coverage, as demonstrated herein, allows detailed structural domain delineation, as well as delineation of even subtle structural sets. The combination of detailed discontinuity set orientation, detailed structural domain delineation, and major structure interpretation allow for optimizing placement of drillholes. Such optimization can result in a reduced number of drillholes required to bring projects such as the Williams Open Pit to the feasibility level of design confidence.

Of course, no data collection methodology should be used in isolation. While not conducted here, the structural model should be adjusted such that it “fits” the exposure. This involves evaluating structural intersections with the individual photogrammetric models as well as, most importantly, field verification and assessment of the model. Further adjustment of the model by evaluation of structural intersections with drillholes and underground openings not only assist in verifying the model but result in a more complete, detailed, and valuable work.

Local mapping of rock fabric is useful to confirm the general conclusions of the large scale structural photogrammetry as well as for bench scale analyses.

The DTM's resulting from the photogrammetry, together with the associated draped images, are extremely useful for evaluating the performance of existing slopes. As was demonstrated herein, one can utilize the models for evaluation of blast damage, effective rock fall catchment and bench face performance, as well as to compare theoretical models with the attained results. In addition, although not shown here, it can be utilized for back analysis of existing failures and to provide detailed as-built geometries for comparison with design layouts.

In conclusion, the resulting photogrammetric models, when properly collected and evaluated, provide a wealth of information regarding not only structural information, but attained slope performance. Both are critical to optimizing design slopes.

8 Acknowledgements

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9 References
