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CLOSE-RANGE GEOPHOTOGRAMMETRIC MAPPING OF TRENCH WALLS USING MULTI-MODEL STEREO RESTITUTION SOFTWARE

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ABSTRACT

Methods for mapping geologic features exposed on trench walls have advanced from conventional gridding and sketch mapping to precise close-range photogrammetric mapping. In our study, two strips of small-format (60 x 60 mm) stereo pairs, each containing 42 photos and covering approximately 60 m of nearly vertical trench wall (2-4 m high), were contact printed onto eight 205 x 255-mm transparent film sheets. Each strip was oriented in a Kern DSR15* analytical plotter using the bundle adjustment module of Multi-Model Stereo Restitution Software (MMSRS). As MMSRS has automatic model-change capabilities, geologic data were digitized from two film sheets (20 stereo models) at one time without the inconvenience of stopping for individual stereo model setups.

We experimented with several systematic-control-point configurations to evaluate orientation accuracies as a function of the number and position of control points. We recommend establishing control-point columns (each containing 2-3 points) in every 5th photo to achieve the 7-mm Root Mean Square Error (RMSE) accuracy required by our trench-mapping project.

INTRODUCTION

Surficial geologic and tectonic studies are critical to the evaluation of faults at Yucca Mountain, Nevada, the site selected for characterization as a potential high-level nuclear waste repository (fig. 1). Excavation of trenches across known and suspected fault traces provides an effective means of exposing surficial and shallow bedrock units for direct examination and study. Present plans call for at least 20 trenches, 20-50 m long and 2-5 m deep, to be excavated across known and suspected Quaternary faults on and near Yucca Mountain. Geologic and structural data must be collected from the walls of these trenches in a timely and objective manner.

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* Any use of trade names is for descriptive purposes only and does not imply endorsement by the USGS.

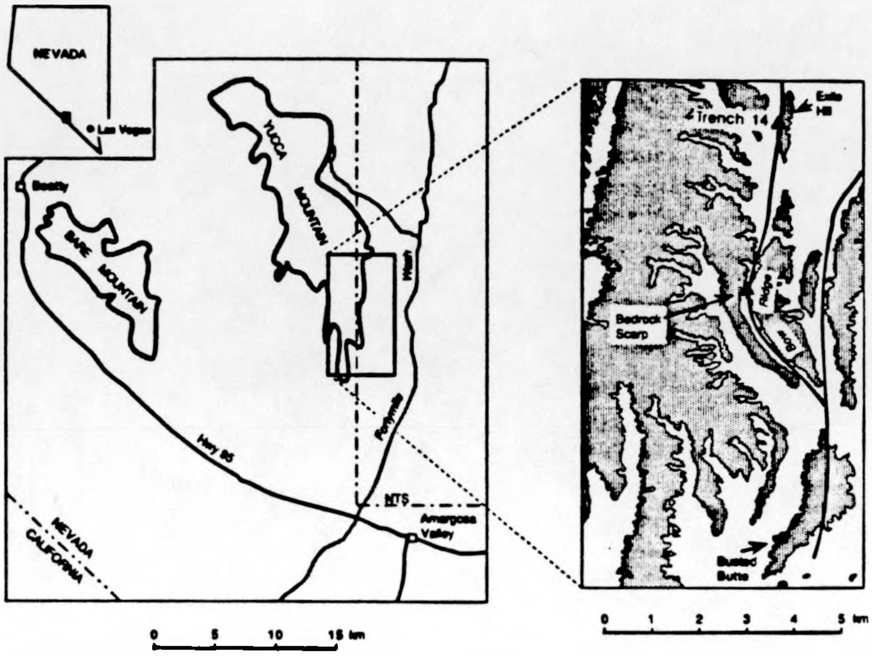

Figure 1. Map showing the location of Yucca Mountain, Nevada and trench 14.

Conventional mapping of trench walls has consisted of measuring geologic features in the field and recording their positions in relation to a rope grid or similar reference system placed on the trench wall. Field measurements and map drafting associated with the technique are extremely time consuming.

The U.S. Geological Survey (USGS) is developing a photogrammetric method for mapping geologic features exposed on trench walls in an effort to make the mapping process more efficient and meet Quality Assurance guidelines. This photogrammetric method, first described by Fairer and others (1989), requires: placing and surveying photogrammetric targets on the trench walls; photographing each trench wall with a calibrated small-format camera to obtain strips of overlapping stereo photos; and orienting the photos to the targets using an analytical photogrammetric plotter. Once the photos are properly oriented in the analytical plotter, three-dimensional data can be collected; structural parameters can be calculated; planar geologic elements can be projected; and geologic features can be observed, measured, and plotted. Initially this method of trench-wall mapping required that a minimum of 4 control points be positioned and surveyed in each stereo model and that each individual stereo model be oriented in the analytical plotter one at a time (Fairer and others, 1989). Using the Multi-Model Stereo Restitution Software (MMSRS) of Dueholm (1990) we find that the number of control points can be significantly reduced and that as many as twenty 60 x 60-mm format models can be oriented and mapped from simultaneously.

Our intention in this paper is to: (1) summarize the field work involved in acquiring the photos and control points; (2) describe the multi-model orientation procedure; (3) present the results of a control-point experiment designed to evaluate absolute cartographic accuracy as a function of the number and position of control points used to orient the photos; and (4) provide an example and conclusions from geophotogrammetric mapping. Absolute cartographic accuracy, as used in this paper, refers to the degree of conformity of point measurements, gathered by photogrammetric means from an oriented strip of stereo photos, to the ground coordinate system being used. All work described herein resulted from prototype testing of the photogrammetric method in a single trench.

FIELD WORK

Target placement, surveying, and photography took place in trench 14 on the east side of Yucca Mountain (fig. 1). Trench 14 trends east-west and is approximately 60 m long, 5 m wide, and 1.5 to 3.5 m deep (fig 2). Trench 14 exposes, from east to west, fractured volcanic rocks, a west-dipping main fault zone consisting of discrete nearly vertical veins within brecciated bedrock, and colluvium and slope-wash alluvium (for a description of the geology exposed in trench 14, see Swadley and others, 1984).

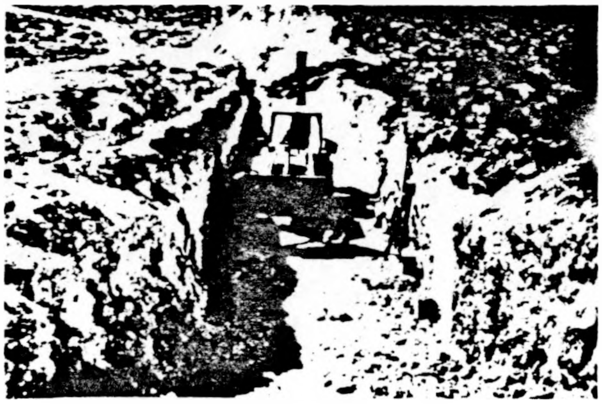

Figure 2. Terrestrial view (from east to west) of trench 14.

Target Placement and Surveying

Columns of targets were mounted on the trench walls every 1.4 m beginning with the first column, which was directly opposite the first camera station. This spacing produced columns of targets on each wall directly in front of each camera station, or one column of targets for each photo taken (fig. 3), and established the maximum number of targets (4-6 per stereo model) needed for the control-point-configuration experiment. Two targets were set in each target column when the height of the trench wall was less than 2.4 m (one half the camera's linear field of view), and three targets were set in each column when the trench height was greater than 2.4 m. The top and bottom targets were placed as close to the top and bottom of the walls as conditions would permit. The middle target, when three targets were needed, was placed at the center of the trench wall. This configuration yielded 103 targets per wall over the 60 m length of the trench. Under production mapping conditions, the number of targets needed will be approximately one fifth this amount (see control-point experiment section).

All targets were surveyed using a Wild electronic laser theodolite and a small-pin-mounted prism. Since all targets were surveyed, any target could be used as a control point or as a ground truth "place-holder point" (to test the accuracy of the photogrammetric orientation) in the control-point-configuration experiment.

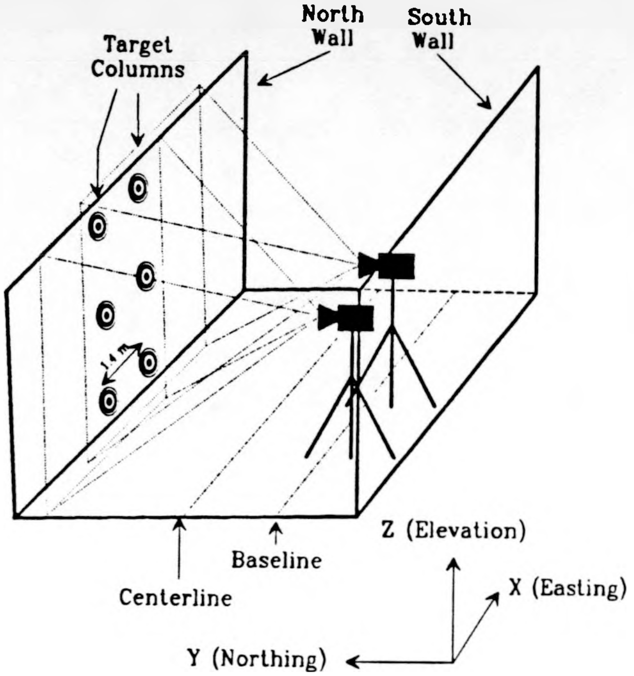

Figure 3. Diagram showing photography setup. Spacing of target columns and camera stations is 1.4 m. Focal length is approximately 40 mm. Camera-to-object distance is approximately 4.0 m.

Photography

A Rollei 6006 camera with a Zeiss 40 mm lens and Kodak VPS color negative film was used for the photography. All photos were taken at night using a Speedtron flash unit to avoid sun shadows and uneven lighting on the trench walls.

Surveyors' ribbon was placed along the floor of the trench (4.0 m from each wall) to mark camera baselines. A camera to trench wall distance of 4.0 m was selected because it left 1 m behind the camera for the photographer to work, produced a workable photo scale (1:100), and yielded a camera linear field of view (4.7 m) adequate to cover the maximum height of the trench (3.5 m).

Seventy percent overlap was used between adjacent photos. To achieve this overlap percentage, the distance between camera stations along the camera baseline was 1.4 m (fig 3). Forty-two photos were required to cover each wall of the trench. Six to nine targets appeared in each photo so that from 4 to 6 targets occurred in each 70 percent overlap stereo model (fig. 4).

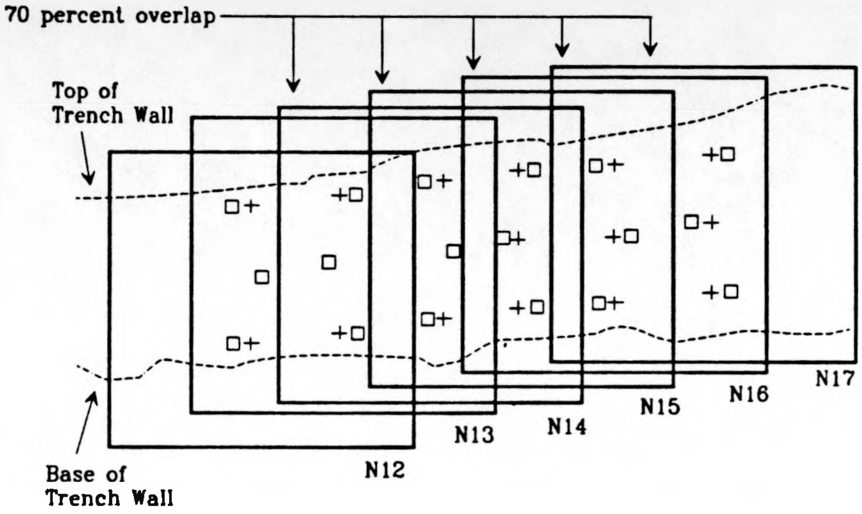

Figure 4. Diagram showing target (+), natural-pass point (□), and photo positions from a section of the north wall of trench 14. Photo numbers indicate the position on the trench wall (ie, the photo strip started with N1 as the leftmost photo). Two targets are positioned at the center of photos N12-N14 and three targets are positioned at the center of photos N15-N17 indicating a change in wall height from less than 2.4 m to greater than 2.4 m. Note: natural-pass points are located and measured in the analytical plotter and do not require positioning in the field.

LABORATORY WORK

Multi-Model Stereo Restitution

Templates. Photo negatives were developed and printed on eight 205 x 255-mm color film transparencies or templates (Dueholm, 1990). Each template contained 9 to 12 alternating left and right photos (figs. 4 and 5) and "reseau-like" marks ("template-tick marks") in each corner. Four templates were used for each trench wall photo strip (fig. 5).

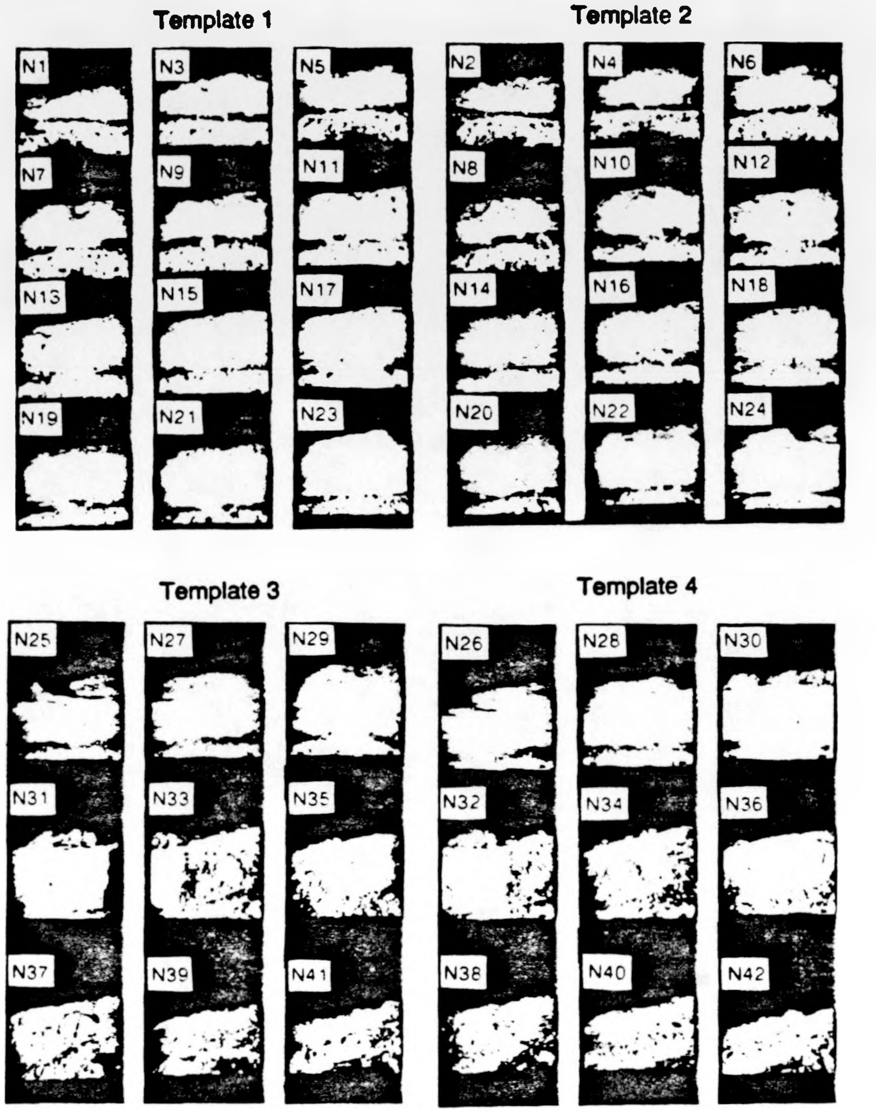

Figure 5. Templates of photos from the north wall of trench 14. Photo N1 is the leftmost photo in the strip and photo N42 is the rightmost. The location of photos shown in figure 4 illustrates the alternating left, right photo organization.

Templates of each wall were oriented in a Kern DSR15[1] analytical stereo plotter using MMSRS. MMSRS orientation is split into three parts: inner orientation consisting of template and individual photo orientations; stereoscopic measurement of targets and "natural" pass points; and exterior orientation of each trench wall photo strip using the bundle adjustment module.

Template and Photo Orientations. Templates were registered in the DSR15's plate coordinate system by measuring the location of the template-tick marks on the stage plates of the plotter. This procedure establishes plate to template transformation matrices. Registration of individual photos to the templates was accomplished by measuring a minimum of 4 reseau marks in each photo (fig. 6), transforming the measurements to template coordinates, and calculating template to photo transformation matrices. This two-step orientation process makes it possible for all of the photos on each template to be oriented as a group. If the photos need to be reoriented at a later date, only the template-tick marks need to be remeasured.

Figure 6. Photo of the south wall center section fault zone encompassing the area photogrammetrically mapped in figure 8. Distance between target columns is 1.4 m. Crosses are camera reseau marks.

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[1] The DSR15 is the DSR11 analytical plotter utilizing a DEC VAX computer and VMS operating system.

Measurement of targets and "natural" pass points. Natural-pass points are natural features on the trench wall that are visible and can be measured in three successive photos. Examples of natural-pass points might include the corner of an angular clast, the intersection of a contact and a fracture, or the intersection of two fractures. Six natural pass points were selected and stereoscopically measured in each 70 percent stereo model overlap area (fig. 4). The location of each natural pass point was transferred from one photo to the next by digital stereoscopic point transfer (Dueholm, 1990). Digital stereoscopic point transfer makes it possible to measure pass points in successive photos without physically marking (pugging) the photos. Each time that a pass point is measured, the location of the point is digitally stored in template coordinates. When the same pass point needs to be measured in the next successive photo, MMSRS locks the DSR15 stage plate on the point in the previously measured photo and allows the operator to stereoscopically measure the point in the new photo by removing x and y parallaxes relative to the locked photo.

Targets were also measured stereoscopically. Each target column occurred in three successive photos, but was only measured in two. This was done to simulate production trench mapping conditions in which targets may only occur in two photos.

Bundle Adjustment Methods. The Generic Bundle Adjustment (GBA) module of MMSRS (Dueholm, 1989) performs a weighted adjustment of photo and surveying observations to determine an exterior orientation for the strip of photos. The GBA uses the inverse square of an a priori error value to weight each observation. The a priori error value is determined by the GBA from the observation standard deviations entered by the user. The two types of observations in this study were photo and survey measurements.

The standard deviation of photo measurements was computed by running the GBA using two XY control points and three Z control points. This configuration created a "no redundancy" solution for the control-point coordinates, therefore, the resulting standard error unit weight, computed by the adjustment, was a measure of the "correctness" of the applied a priori error on photo measurements. The standard deviation was modified after successive GBA runs until the standard error unit weight calculated by the GBA was equal to 1.0. In this manner, the photo measurement standard deviation was found to be 6 micrometers.

The standard deviation for the surveyed target coordinates (X, Y, and Z) was determined by using all 103 targets as control points in a GBA calculation with the photo measurement standard deviation set to 6 micrometers. The standard deviation of the surveyed target coordinates was modified after successive GBA runs until the standard error unit weight equaled 1.0. In this manner, the standard deviation on surveyed target coordinates was found to be 2 mm.

Control-Point-Configuration Experiment

MMSRS provided the opportunity to experiment with control-point configurations that would minimize the number of surveyed targets, reduce the time spent in the trench, and maintain acceptable accuracy. Acceptable accuracy for our trench mapping project is that specified in the USGS study plan for evaluating Quaternary faulting at Yucca Mountain (Shroba and others, 1988). The study plan calls for locating geologic features exposed on trench walls within a maximum measurement error of ±2 cm. A root mean square measurement error (RMSE) of approximately 7 mm is necessary to meet this requirement.

The control-point-configuration experiment involved selecting systematic-control-point configurations, running the bundle adjustment with the selected configurations, and evaluating the results. Surveyed targets and photos from the north wall (fig. 5) were used in the experiment.

Selection of Control-Point Configurations. Selection of control-point configurations was based on the need for systematic/symmetrical control-point distributions that would minimize systematic errors. Configurations that contained control points at the ends of the photo strip were necessary to avoid uncontrolled error propagation. To meet these criteria, selected control-point columns were removed to create successive configurations, each with systematically fewer control points than the previous configuration.

Ten configurations (table 1) were selected for evaluation. Configuration 1 has control-point columns every 1.4 m, or one control-point column in every photo. Configuration 2 has control-point columns every 2.8 m, or one control-point column in every other photo. The remaining configurations follow this general trend, but are restricted by the need to maintain both systematic and symmetrical configurations within the photo strip.

The entire set of natural-pass points was used in all the control-point configurations evaluated. Depending on the configuration, measured targets were used either as control points or as place-holder points in bundle adjustment calculations. Using targets as place-holder points allowed for a comparison of calculated coordinates of target positions with the surveyed coordinates. Place-holder points have no affect on exterior orientation results and under normal mapping conditions these points would not be present.

Bundle Adjustment Runs and Calculation of Results. Each of the ten control-point configurations was run through the GBA using the appropriate standard deviations for photo and survey measurements (6 um and 2 mm, respectively). After each run, adjusted values for control points and place-holder points were compared to surveyed coordinates and RMSE values were calculated (table 1).

<u>Discussion of Control-Point Experiment Results.</u> All of the surveyed targets were used as control points in configuration 1. This configuration produced the maximum accuracy achievable for the strip of photos. As seen in table 1, the RMSE values from configuration 1 were less than or equal to 2 mm in each of the X, Y, and Z directions. In general, for configurations 2, 4, 5, 6, 7, 8, 10, and 20, RMSE values in the X and Y directions gradually increased and RMSE values in the Z direction stayed constant as the number of control points decreased (see table 1, fig. 7). RMSE values for all coordinates from these configurations were less than or equal to 18 mm. The results from configuration 40 indicate a significant increase in all RMSE values when compared to the results of the other configurations (table 1, fig. 7). Such an increase in RMSE values indicates a configuration that creates unstable GBA results.

Configurations 7, 8, 10, 20 yield RMSE values greater then the RMSE requirement of 7 mm or less. Configurations 1, 2, 4, 5, and 6 produce RMSE results that meet the 7 mm requirement. Of these, configuration 5 is recommended for future use. Configuration 5 (control-point columns in every 5th photo) produced RMSE values less than or equal to 6 mm in the X, Y, and Z directions and contains fewer control-point columns than configurations 1, 2, or 4. In addition, based on the results from configuration 6, which are slightly better than configuration 5, a limited number of control points could be dropped out of configuration 5, and the 7 mm RMSE accuracy requirement would still be met.

Configuration (Target columns in every nth photo used as control points)	Number of control points in configuration	Number of photos in configuration	RMSE (meters)		
			X	Y	Z
1	103	41	0.002	0.002	0.001
2	53	41	0.002	0.003	0.002
4	27	41	0.003	0.005	0.002
5	21	41	0.003	0.006	0.002
6	17	37	0.003	0.004	0.002
7	15	36	0.004	0.008	0.002
8	15	41	0.004	0.009	0.002
10	12	41	0.006	0.010	0.002
20	7	41	0.011	0.017	0.002
40	4	41	0.015	0.279	0.088

Table 1. Control-point configurations and RMSE results from the control-point-configuration experiment.

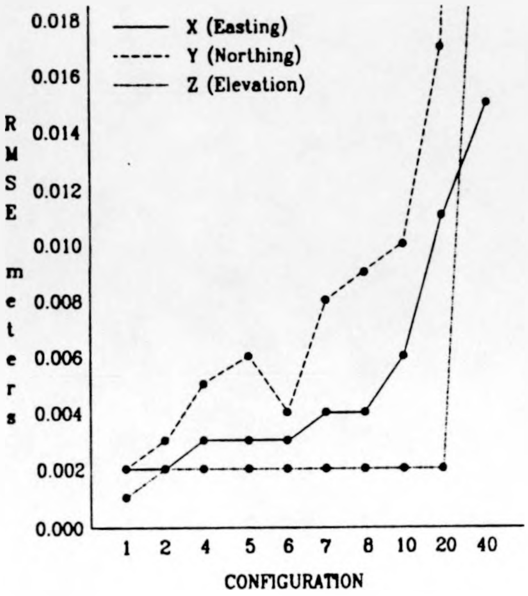


Figure 7. RMSE values plotted as a function of the configuration used. Results from configurations 1, 2, 4, 5, 6, 7, 8, 10, 20, and 40 are shown. X (easting) is horizontal and parallel to the trench wall, Y (northing) is horizontal and perpendicular to the trench wall, and Z (elevation) is vertical and "up and down" the trench wall.

Geophotogrammetric Mapping

The photo strip from the south wall was used for mapping. The GBA was run using all the targets on the south wall as control points. The exterior orientation results from this GBA run were downloaded to the plate processor.

Once the exterior orientation has been downloaded, two templates of photos (one template on each stage plate) may be used for mapping at the same time. The plate processor controls the movement from one stereo model to the next. The plate processor movement or "jump" to the next model is based on the dimensions of the photo frames previously defined by the user. When the measuring mark is moved across the edge of either of the photo frames of the current model the plate processor jumps to the same ground coordinates in the next model. This automatic movement between models makes it possible to digitize data continuously across model boundaries. For example, if a geologic contact runs the entire length of the trench wall, ground coordinate data can be continuously collected along the contact from the twenty models oriented in the DSR15; without stopping to manually change individual models. This provides an extremely powerful and flexible tool for geologic investigations.

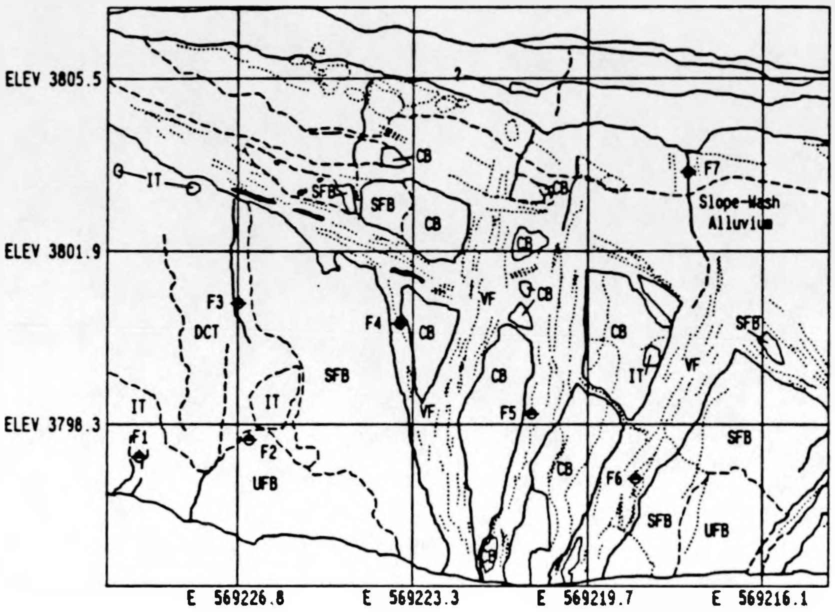
The goals of our photogrammetric trench mapping project were to: collect three-dimensional line work delineating fractures, contacts, veins, etc.; calculate attitudes of fractures and internal bedding features using the three-dimensional line work points; and project and plot data on a two-dimensional strip map. Data plotted on the strip map must appear the same as if the viewer were standing in the trench looking directly at the wall. Therefore, an orthographic projection, with data plotted on a vertical plane running parallel to the trench wall, was used. GEO-PROGRAM software (Dueholm and Coe, 1989) was used to collect and project the data, attitudes were calculated by GEO-PROGRAM using the three-dimensional points and a least squares adjustment. Detailed editing and plotting was done using Kork Digital Mapping System software.

The most geologically complicated section of trench 14, the south wall center section (fig.6), was mapped photogrammetrically using GEO-PROGRAM (fig. 8). This section of trench wall exposes the west-dipping main fault zone. The geologic features most readily mapped photogrammetrically are those that have a high degree of contrast and/or relief in relation to their surroundings. For example, the bedrock bounded veins (figs. 6 and 8) are extremely visible in the photographs due to their light color in comparison to the surrounding bedrock. Fractures are easily located due to the relief common along their exposed surfaces. Fractures that lack an adequate surface on which to set a brunton compass during field mapping are easily mapped photogrammetrically due to the "vertical" exaggeration that stereo models provide. In addition, the attitude of a fracture can be calculated using three-dimensional points collected from along the fracture's entire trace length, as opposed to a "single point" attitude measurement taken with a brunton in the field.

Many physical features such as soil texture, a measure of the particle size distribution, and concentration and distribution of secondary calcium carbonate are too subtle for photogrammetric interpretation and must be determined by field observation. Subtle variability in the bedrock units also must be determined in the field. Each investigator must decide the field technique that best compliments their photogrammetric interpretations. This may include either marking or flagging contacts on the trench walls before the photos are taken, or mapping on the photos in the field. However, there is no question that field checking of the geophotogrammetric map is a requirement of photogrammetric trench wall mapping.

SUMMARY

MMSRS makes it possible to orient, and photogrammetrically map from, multiple small-frame stereo models (up to twenty 60 mm trench wall models at once) without having to mark (pug) pass points or interrupt digitizing of geologic features to orient individual models. The number of simultaneously oriented models is not limited by MMSRS but by the physical size of the analytical plotter's stage plates. For example, with 230 x 460-mm stage plates, up to 44 60-mm stereo models can be oriented and mapped from simultaneously.



EXPLANATION

— LITHOLOGIC UNIT AND SOIL-HORIZON BOUNDRIES--
Dashed where transitional

CARBONATE STRINGER

CARBONATE PLATELETS

— OPALINE SILICA STRINGER

— FRACTURES--
Dashed where approximately located

◆ ATTITUDE MEASUREMENT--

Label	Amount of Dip	Dip Direction
F1	86	318
F2	81	250
F3	89	249
F4	89	245
F5	88	300
F6	76	110
F7	88	273

VOLCANIC ROCKS

IT--INTACT SLIGHTLY FRACTURED TUFF

DCT--DENSELY CARBONATE-CEMENTED AND FRACTURED TUFF

FAULT ZONE--BRECCIA AND VEIN FILLING

UFB--UNCEMENTED FAULT BRECCIA

SFB--SILICA-CEMENTED FAULT BRECCIA

CB--CEMENTED CATACLASTIC FAULT BRECCIA

VF--VEIN FILLING

Figure 8. Photogrammetrically compiled map of the south wall center section of trench 14. Orthographic projection looking south. Coordinate system is Nevada State Plane. Units are in feet. Easting coordinates decrease from left to right and elevation coordinates increase from bottom to top of trench.

Based on control-point configuration experimentation with a single strip of trench wall photos, a control-point column placed in every 5th photo results in a coordinate RMSE of 6 mm or less. The first and last photos should always contain a column of surveyed targets to avoid uncontrolled error propagation.

Although this photogrammetric method cannot replace geologic field investigations, it is an invaluable mapping tool that provides an objective, detailed record of geologic exposures. Application of the method is not limited to mapping geologic features on trench walls. Any accessible vertical or near vertical rock exposure can be photographed and mapped using the methods described herein. The method is also applicable to inaccessible exposures with sparse ground control information (Dueholm and Pedersen, 1990).

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