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Fracture Mapping at the Spent Fuel Test—Climax

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FRACTURE MAPPING AT THE SPENT FUEL TEST--CLIMAX

ABSTRACT

Mapping of geologic discontinuities has been done in several phases at the Spent Fuel Test--Climax (SFT-C) in the granitic Climax stock at the Nevada Test Site. Mapping was carried out in the tail drift, access drift, canister drift, heater drifts, instrumentation alcove, and receiving room. The fractures mapped as intersecting a horizontal datum in the canister and heater drifts are shown on one figure. Fracture sketch maps have been compiled as additional figures. Geologic mapping efforts were scheduled around and significantly impacted by the excavation and construction schedules. Several people were involved in the mapping, and over 2500 geologic discontinuities were mapped, including joints, shears, and faults. Some variance between individuals' mapping efforts was noticed, and the effects of various magnetic influences upon a compass were examined. The examination of compass errors improved the credibility of the data. The compass analysis work is explained in Appendix A. Analysis of the fracture data will be presented in a future report.

INTRODUCTION

The Spent Fuel Test--Climax (SFT-C) at the Nevada Test Site is a demonstration of the feasibility of safe and reliable short-term storage and retrieval of spent reactor fuel assemblies at a plausible repository depth in granite. A secondary purpose of the SFT-C is the acquisition of technical data pertinent to the use of hard rock as host media for nuclear waste repositories. Carlson et al.¹ presented a summary of the use of the SFT-C for this purpose.

This paper deals with one part of the geotechnical program of the SFT-C; i.e., the mapping of geologic discontinuities in the SFT-C underground facilities. Wilder and Patrick² have summarized other selected aspects of the geotechnical work to date, and additional related publications are planned or are in various stages of preparation. These include an analysis of data

from the fracture mapping presented herein, a report briefly treating many of the geologic considerations necessary for design and modeling of the facility, an overview of the geology of the SFT-C, documentation of the geotechnical instrument installation and maintenance, and analyses of the data obtained by the instrument systems. Thorpe and Springer³ reported on mapping in the Climax stock for the Radionuclide Migration program.

SPENT FUEL TEST--CLIMAX, PHYSICAL DESCRIPTION

DESCRIPTION OF UNDERGROUND FACILITIES

The general layout of the underground SFT-C facilities is shown in Fig. 1. The designated previously existing workings include tunnels and a shaft with hoisting equipment. These were originally constructed for nuclear

FIG. 1. Spent fuel test layout.

weapons effects tests conducted in the 1960s. A 12-ft $\times$ 12-ft (3.7 m $\times$ 3.7 m) access drift runs from the older workings to the railcar room. There it branches into a 15-ft-wide $\times$ 20-ft-high (4.6 m $\times$ 6 m) canister drift and two 11-ft $\times$ 11-ft (3.4 m $\times$ 3.4 m) heater drifts. As illustrated, these then diverge and run parallel for nearly 200 ft (60 m) until they converge into the receiving room. The canister access hole penetrates the roof of the receiving room from the ground surface which is about 1375 ft (420 m) above. A 12-ft $\times$ 12-ft (3.7 m $\times$ 3.7 m) tail drift also extends from the older workings (this can be used for future scientific experiments), and an instrumentation alcove lies between the tail drift and the railcar room.

SUMMARY OF CONSTRUCTION SEQUENCE

Excavation for the SFT-C was carried out in an orderly sequence to precisely locate the canister access hole before driving the center drift, and to allow the rock deformation to be measured as mining progressed. First, the tail drift was partially completed. Then, the access drift from the older workings to the railcar room was completed. Finally, the railcar room was partially excavated. The heater drifts then were driven to intersect the access hole which had been drilled from the surface. Afterward, the instrumentation alcove was opened and the tail drift extended, followed by the excavation of the canister drift using a top heading and bench method.

GEOLOGIC SETTING

The geology of the Nevada Test Site (NTS) region consists of complexly folded and faulted sedimentary rocks of Paleozoic Age; these are overlain by Tertiary volcanic tuffs and lavas, with Tertiary and Quaternary alluvium in the valleys. The Yucca Fault, a prominent north-south trending fault with geologically recent offsetting, has formed a conspicuous topographic scarp in northern and central Yucca Flat (see Fig. 2). Two other major faults in the vicinity of the Climax stock are the Tippinip Fault and the Boundary Fault (see Fig. 3). The Tippinip Fault is located west of the Climax stock and trends north-northeast. The Boundary Fault forms the southeast contact

FIG. 2. Nevada test site geology.

FIG. 3 Climax stock geology (modified from Ref. 5).

between the stock and alluvium; it also trends northeast. The Yucca Fault is located south of the stock, trends northward, and possibly joins the Boundary Fault along the southern margin of the stock.

The Climax stock, a composite granitic intrusive body located at the north end of NTS, outcrops over an area of about 1.6 mi² (4 km²) (see Fig. 3). Allingham and Zietz⁶ present geophysical evidence suggesting that the stock expands conically to an area of about 100 km² at a depth of several kilometers. The granitic stock is composed of two main units, granodiorite and quartz monzonite, which contain varying proportions of the same minerals. Grain-size diameters in both units range from 1 to 4 mm. However, the quartz monzonite contains scattered large pink alkali feldspar crystals up to 50 mm in length. The quartz monzonite of the Climax stock is moderately-to-highly jointed with three prominent joint orientations reported by Maldonado.⁷ It is in this quartz monzonite unit that the Spent Fuel Test is located.

GEOLOGIC MAPPING

Mapping of discontinuities in the Climax stock proceeded in several phases. The first phase of mapping reported in technical literature was that performed at various times for nuclear weapons effects tests. Specifically pertinent to the SFT-C was mapping done in the Piledriver drifts.

The second phase of mapping was conducted as excavation proceeded for the SFT-C. This planning phase mapping was limited to the tail drift, portions of the instrumentation alcove, and the south rib of the main access drift leading into the SFT-C complex. Typically, the mapping was done by project engineering geologists working individually. The intention of this second phase of mapping was threefold: 1) to compare the attitudes of features in the tail drift and the SFT-C area with features reported for the Piledriver drifts, and to confirm that fracture attitudes which had been interpreted in the core borings were basically correct; 2) to define which geologic features needed to be mapped within the project and at what level of detail; and 3) to identify those features which would project into the area of the SFT-C and which might be of concern. This phase of mapping continued during the excavation of heater drifts whenever it could be performed without interrupting construction and when the project engineering geologists involved in other aspects of the program were available. The mapping was delayed to allow core logging of instrumentation holes, to select anchor locations for extensometers, and to work on the mine-by instrumentation. Core logging and mine-by instrumentation activities continued until the canister drift excavation began.

After the canister drift was excavated, a third phase of mapping was undertaken. This phase consisted of mapping of the canister drift invert (floor) and ribs (walls) during a weekend period. Field work was conducted by four teams of two people, the teams generally consisting of a trained geologist or engineering geologist working with an individual from one of several other backgrounds (i.e., environmentalists, mining engineers, computer modelers, and technicians). During this exercise, joints, shear zones, and faults were traced to the extent possible across the canister drift invert. Mapping of the ribs was performed in the same manner as had been done in the mapping of the ribs in the tail drift and the electrical alcove; i.e., specifically as a tape line survey at the five foot elevation. Descriptions of the features intersected by the tape line were recorded.

The objectives of this weekend mapping phase were: 1) to describe, as fully as was practical before the invert rock was covered up by a poured concrete floor, the fracture system and mineralogy of the canister drift (particularly where the spent fuel would be placed); and 2) to identify shear zones and major features that projected through canister emplacement holes to be drilled in the invert. This information was deemed critical to the future understanding of how the rock responded to the thermal and radiation perturbations to be applied. There was no intention to use the geologic mapping to select canister locations, however, since the locations were predetermined by the alignment of the tracks and by the spacing between canisters necessary to keep thermal loads within design limits. Thus, canister locations were dictated by engineering rather than geologic considerations. A final and overriding objective was to finish the mapping within one weekend to prevent adversely impacting the construction schedule.

After the canister drift was mapped, the final phase of mapping was performed. This included detailed mapping of all ribs in the heater drifts and receiving room. Mapping was carried out both during construction and after much of the construction was finished, including the installation of wire mesh, cable trays, overhead conduits and lights, and ventilation access control bulkheads. This mapping was conducted in several ways, but typically by one or two engineering geologists working individually. More specific description of various segments of the mapping are provided in subsequent sections.

It had been recognized early in the program that use of data from the discontinuity mapping would be highly dependent upon the orientation of the drift in which the mapping was done; therefore, it was intended that mapping results would be normalized for drift orientation. Although the SFT-C complex itself tends to be oriented in one direction, there were three sources of data located nearly perpendicularly to the main SFT-C drift orientation. The first of these was the instrumentation alcove, which was oriented nearly 90° from the project axis. Second, the tail drift centerline was about 43° from the project axis orientation. Third, the curved sections of the heater drifts and the receiving room were also at significant angles from the project axis. To provide a basis for comparing joint frequencies for features striking predominantly northwest with joint frequencies for features striking predominantly northeast, mapping in these areas could be used with the core logs from mine-by and instrumentation holes, which were at approximately right

angles to the project axis. It was recognized that the normalization process and much of the manipulation needed to sort and analyze data by joint infilling, by type of fracture, and by other characteristics, would require a computer-based data system. An attempt was made to obtain a computer program which would plot the data as desired, but available programs have not been fully implemented at this time. Therefore, much of the information currently available does not include stereonet, except for the tail drift stereonet which were done by hand.

TAIL DRIFT MAPPING

The tail drift was mapped as the excavation proceeded in order to find the frequency and orientation of jointing and faulting, to compare the attitudes of these features to those that had been previously mapped in the Piledriver drift, and to get a general estimate of the type of features that would be intersected by construction in the SFT-C area. These features were described in terms of their orientation as determined by the use of a Brunton compass and in terms of their general characteristics. Wherever possible, the orientations of features were measured from the center of the drift (between the rails), using sighting techniques. Otherwise, measurements were made at the rib surface. When it was impossible to determine the strike, an apparent dip and surface orientation was recorded. The magnetic declination was checked periodically by sighting down the centerline of the tail drift to determine whether the known orientation of the tail drift was read properly on the Brunton compass. Although these readings on drift orientation were not recorded, if the bearing of the tail drift was significantly different from the bearing measured by the Brunton compass, the difference was applied as a correction factor to the strike readings made in the vicinity of the observed discrepancy.

In order to describe the features that were present, it was necessary to wash the ribs as the mapping progressed. Because the mapping was being done concurrently with excavation, the cleanliness of the ribs constantly deteriorated between washings. This was particularly true since the drill jumbos tended to create noticeable quantities of oil and water mist containing rock flour. This caused the mapping to be of somewhat uneven quality, so the engineering geologist would decide when the ribs needed to be rewashed. The mapping in the tail drift was performed using a miner's cap lamp making the

lighting conditions less than ideal for identifying very small geologic features.

Survey control was not generally available in the tail drift. Stationing was determined by the engineering geologist with a hand held tape. Because the ribs were irregular, the best that could be done was to judge a straight line along the ribs. Since the engineering geologist was often working alone, it was necessary to take small increments in stationing (whatever could be reached by holding both ends of the tape). Therefore, there are likely to be inaccuracies in stationing of mapping done in the tail drift.

MAIN ACCESS DRIFT MAPPING

Mapping of the main access drift was performed by techniques similar to those described for the tail drift. The purpose was to obtain correlations with features mapped in the tail drift, where possible. This mapping also was done concurrently with the excavation process. However, once mining of the heater drifts commenced, two faces were mined simultaneously, which created a heavy mucker traffic pattern in the access drift. This interfered with the mapping; therefore, mapping was done only on the south or left rib.

HEATER DRIFT MAPPING

Mapping in the heater drifts was done in three stages. As the heater drifts were being excavated, a walk-through identification was made of major features, with particular attention given to shear zones. This first-stage mapping information was used as a basis for locating instrumentation so that selected instruments would intercept major joints or shear zones. Typically, this stage of mapping was done on a project engineering map and relied on a Brunton compass for joint orientations. The survey control that was provided periodically to the drill jumbos (usually the stationing of the working face) and the engineering geologist's tape surveys along the rib were used to control the walk-through mapping. Often, the Brunton compass was used as an inclinometer and protractor rather than as a compass because of the intimate presence of the drill jumbo. When used as a protractor, the Brunton was rotated from a position of alignment with the drift centerline to a position in line with the strike of the given feature, thus providing the angle between the two.

Early project drawings indicated a symmetrical layout, with the heater drifts spaced equally on either side of the canister drift. After the access hole was drilled and surveyed, it was decided to change the orientation of the drifts slightly to properly align the drifts with the access hole. In addition, after the heater drifts intersected the access hole, it was determined that a slight offset of the canister drift was necessary. The canister drift was not equally spaced between the two drifts, therefore, and the layout was not quite shown as on the original project plans. These modifications caused some inaccuracies in the original walk-through mapping which was done prior to general availability of new maps. This gave rise to problems in projecting features from one drift to another. However, the problem was recognized by the project engineering geologist, and appropriate allowances were made by sketching approximate drift location corrections on the old maps. Although these inaccuracies were corrected before more detailed mapping was conducted, they were of concern in the selection of mine-by-instrumentation locations. Shear zones had been projected to their intersection with the canister drift, and instruments had been located relative to these projections. Subsequent mapping has shown that the projections were off by a foot, at most.

The second stage of mapping attempted in the heater drifts was similar to that which had been done in the tail drift. However, this effort was quickly abandoned because of a pressing need to log core and to select instrument locations and extensometer anchor points.

The third stage of mapping conducted in the heater drifts was carried out after excavation of the heater and canister drifts was complete. The canister drift mapping had also been completed at this point and is described below. Much of the heater drift construction had been completed before this mapping was started. This included the placement of a sand blanket on the invert; the installation of permanent fan lines, lights, and overhead structures; and the erection of wire mesh and steel channel supports along the ribs. Therefore, this mapping was done under conditions of restricted visibility and in proximity to magnetic influences (see Appendix A). In an effort to complete the mapping before additional steel channel and electrical fixture installation could cover up the ribs, several people were used to do the mapping. However, this work eventually fell to only a few individuals, generally those employed by California State University at Hayward. They did the majority of the detailed field work in the heater drifts.

Inefficiencies in heater drift mapping were created while trying to meet construction schedule constraints. Mapping would start in one drift to allow construction activities to proceed in the other drift. Then, mapping would shift from one drift to the other to allow construction activities to shift. This prevented mapping of an entire rib or section as an entity. Also, at times construction crews occupied both drifts. Ventilation lines were taken down, lights were constantly changing, and dust levels and control sprays varied according to construction activities. As a result, the mapping conditions were not uniform and the accuracy of the effort varied. Mapping quality in the heater drifts also varied because of the large number of people involved; however, this source of variability was largely eliminated towards the end of the program when only a few individuals or, quite frequently, a single individual was involved.

During the early part of this stage of mapping, the ribs were washed and mapping was done under cap-lamp conditions augmented by portable quartz-halogen lamps. Later portions of this stage of mapping were completed with the aid of incandescent lights along the crown (roof) of the drift which were occasionally augmented by portable quartz-halogen lamps. During these later stages, an attempt was made to control the amount of water introduced into the drifts; therefore, the ribs were not washed down by hosing. Two techniques other than direct washing were used to clean the rib being mapped. One was to direct a compressed air stream towards the rib, then to pour a small volume of water from a cup into this air stream. This would moisten the rib, bring out the features, and, to some limited extent, clean the rib. The other technique was to moisten the rib by the use of a portable 5-gal pesticide-type sprayer. Very little actual washing was expected, and none took place; however, it was found that moistening was fairly effective in bringing out features for a short period of time so that they could be seen more readily.

The mapping was performed by the use of a Brunton compass. Where metal objects were present, a reading of drift orientation was made and compared to actual orientation so that corrections to readings could be made. The Brunton compass was sometimes used merely as a protractor in measuring the angle between the drift orientation and the joint strike. Mapping in the heater drifts was done at approximately eye level, usually at the level of the steel channel where it was present. No continuous elevation control was available

from the surveyors; therefore, the elevation is not constant. Survey control was marked on the ribs and channel by the mapping parties using a tape. In curved sections it was necessary to do some approximating to correct stationing. This method may not have been accurate, particularly on the inside of the curves.

CANISTER DRIFT MAPPING

So that the SFT-C construction could proceed on schedule, it was necessary to map the canister drift as soon as excavation was completed. This mapping was accomplished in two twelve-hour shifts on a Saturday and Sunday by four crews consisting of a trained geologist working with a professional or technician. In the case of one crew, both crew members were trained in geotechnical engineering. The project engineering geologist provided overall supervision of these four crews by rotating between the crews to assure some consistency, to coordinate the mapping effort, and to provide logistics and obtain contractor support.

The invert and the ribs were washed prior to the beginning of mapping. This was attempted initially by washing the invert, then using a compressed air stream to blow the muck and excess water up grade (because of the ventilation air-flow direction) to the receiving room. Since this splattered muck on the ribs, the ribs would be washed down again, and the process repeated. This was attempted several times with some general improvement in the cleanliness of ribs and invert but without sufficient improvement for mapping. Also, because no effort had been made to bar loose rock from the invert, each blowing cycle would loosen sizable slabs of rock, which then had to be removed by hand. Therefore, rather than to blow out the excess, it was decided to wash the ribs and invert and to pump out the excess water where possible. The remaining water was left sitting as puddles in the invert's low spots.

The invert had not been finished to a smooth grade but was left in the rough undulating condition that resulted from benching operations. The radiation shield pits were not excavated nor had the canister emplacement holes been drilled. However, blast holes had been drilled and plugged in the invert for later placement of explosives to excavate the pits. The location of each canister-emplacement hole was surveyed to provide stationing control

every 10 ft. A similar stationing was marked on the ribs, and a line of constant elevation was established to account for the 0.5% grade of the invert. This line began approximately 5 ft above the invert in the railcar room and dropped gradually to approximately 3-1/2 ft above the invert in the receiving room. This allowed a horizontal plane to be used for the rib mapping so that a plan view map could be prepared showing features on the rib. This was especially necessary because of the variability of invert elevation from point to point within the drift described above.

As features were mapped, they were marked in the field with orange spray paint so that they could be seen easily during the fracture sketching and readily identified in the future. Any new cracks that formed or any existing cracks that had not been mapped could be distinguished by lack of paint. Also, the paint facilitated photographic documentation. An early suggestion to do the mapping only from photographs was rejected by the engineering geologist, but it was decided to photograph the invert and the ribs to record the actual fractures that existed. Invert photographs were taken from the crown using a 35-mm camera mounted on a cable system. Rib photography was accomplished using a hand-held 35-mm camera. Because the cable was approximately 19 to 20 ft above the invert, it was felt that small unmarked features would not be readily picked up by the camera; therefore, photography was delayed until Sunday when most of the features were painted. The photographic work was done by NTS staff photographers. Although some distortion occurred at the edges of the film, the invert photographs provided a direct overhead view of features.

At the time of mapping, wire mesh had been placed over the ribs and crown to within approximately 6 ft of the invert. However, sufficient portions of the rib were exposed to allow mapping directly on the rock rather than through wire mesh. The lighting conditions during the mapping of the canister drift were generally good. Several portable quartz-halogen lamps were placed in the drift and were moved about, as needed, to provide lighting on the areas being mapped by the individual crews. There were approximately two to three of these lights available for each 50-ft section to be mapped. Lighting was supplemented through the use of miner's cap lamps. These cap lamps were particularly useful not only to augment the light from the quartz-halogen lamps but also to allow highlighting and tracing of features on the crown and spring line from one rib to the other.

Features that were identified on the ribs by one mapping crew were not described by the adjacent mapping crew; therefore, many low angle joints which were through-going and continuous were sketched only as a line segment by the crew that actually mapped them. Notes were usually made or intended to be made in the comment section of the field notes when those features were continuous. Where joints could be traced from one rib to another, they were so identified. Frequently, it was not possible to trace the joints. However, shear zones were traceable from one rib to another and were traceable across the invert; furthermore, many appeared to be continuous between drifts.

While an attempt was made to maintain uniformity of mapping by the four crews, the level of detail and, possibly, the accuracy of the mapping varied from crew to crew. This variability exists for several reasons, among which are the experience level and judgment of the mapper and the note taker, their attention to detail, and the location of the mapped section, particularly since the cleaning of the invert and ribs was done from the railcar room towards the receiving room. The section from Stations 3+50 to 4+00 had a significant number of standing puddles of water. Towards the very end, this section still had a fair amount of muck masking the features.

DISCUSSION OF RESULTS

EXCAVATION EFFECTS ON MAPPING

The excavation and construction of the SFT-C have been documented by Patrick and Mayr.⁸ The drifts were mined by drill and blast operations, which affected the mapping in several ways. These effects included overbreak and fracturing caused by blasting, masking of fractures, and interference with mapping operations caused by the construction schedule. The latter problem will be discussed in a subsequent section. Potential compass errors caused by steel ground support components and mining equipment also will be covered in a later section.

Several factors caused the overbreak and fracturing mentioned by Patrick and Mayr.⁸ The hardness and strength of the rock and the lack of experience of the miners with tunneling in granite were two of the more significant influences. The fracturing caused by the blasting gave rise to problems in

discerning naturally occurring fractures from those induced by blasting. Such discrimination was made in the SFT-C mapping on the basis of the mappers' experience and their understanding of the likely appearance, extent, and orientations of the induced fractures. If a question existed, the feature was mapped as questionable.

During excavation and construction, visual masking of the fractures occurred in two ways. First, the construction environment was generally dirty with oil and water mist, diesel engine exhaust, blast fumes, and dust hanging in the air. The mist and dust tended to settle onto the ribs, and mud was splashed onto the ribs from the invert. The rock surface was washed prior to mapping, as time allowed, in an attempt to alleviate the problem. Second, steel mesh (similar in appearance to rusty chain link fence) was placed over the surface of the crown and ribs of the drifts, except for the tail drift. The tightness of the mesh combined with uncertain lighting made mapping difficult. This problem could not be alleviated and required extra care and time in mapping.

SOURCES OF COMPASS ERROR

A problem with using a compass for fracture orientation measurements in an underground work environment is that magnetic errors may be induced by ground support components such as rock bolts and steel mesh; by miscellaneous metal, wires, and utilities; and by equipment such as drill jumbos. During the SFT-C mapping, efforts were made to minimize these errors by keeping the compass away from iron and steel materials and equipment, as described in the discussion of mapping techniques, above. When time permitted and subsequent to the SFT-C mapping several measurements were carried out to obtain a quantitative estimate of the effects of steel mesh, rock bolts, and mining equipment on compass measurements in the drifts. The analysis of these trial measurements is presented in Appendix A. Table 1 below summarizes the results.

EXCAVATION SCHEDULE AND TEAM MAPPING

Time and personnel constraints required using several people in addition to the authors to do the mapping. Most of these people are credited in the acknowledgments section. The canister drift was mapped by four teams of two

TABLE 1. Sources of magnetic compass errors.

Error source	Approximate range for source to induce error	Apparent effect on compass
Steel mesh	Measurements within 1 ft of mesh-covered rock surface.	Needle tends to point at mesh-covered rock surface.
Rock bolts in plane of compass needle	Measurements within 1-1/2 ft of bolt.	Needle tends to point to rock bolt.
Rock bolts offset diagonally above or below needle plane	Unknown, measurements within 1 ft.	No effect noted for bolts as close as one foot diagonally.
Mining equipment (drill jumbo)	Measurements within 2 ft of jumbo.	Needle tends to point to equipment.
Pipe, steel rails on invert	Unknown, invert was 4 to 5 ft below measurements.	No effect noted.
Steel ribs or arches ^a	All measurements in error.	Needle tends to point to steel rib and shows systematic error.

^aNo steel arches were used in the SFT-C drifts. This information is from measurements in the Piledriver drift and is included for completeness.

individuals each. Using many people in structural geologic mapping minimizes the impact of any individual bias on the overall fracture data set. However, it introduces the problem of varying levels of expertise and observational skills among the mappers. Table 2 shows mapping results from six different 50-ft scanlines as recorded in the field notes. Each is taken from the north rib of one of the heater drifts or the canister drift; therefore, all six are parallel in orientation. The six scanlines represent the work of six different individuals or teams of individuals.

Obviously, different mapping teams saw differing numbers of fractures within their given 50-ft scanline. Several factors may account for this: the ribs mapped may have been dirtier at some locations than at others, the mapping teams may have differed in skill or speed, or the fracturing actually present may differ from place to place within the SFT-C drifts. The first two of these three factors are likely to be true; the third will be examined in subsequent data analysis. It is interesting to note, however, that the

TABLE 2. Results of team mapping for six parallel 50-ft scanlines.

Scanline/team	Fractures measured by mapping team		Total
	Number dipping over 45°	Number dipping 45° or less	
1	46	18	64
2	20	28	48
3	47	28	75
4	37	31	68
5	22	24	46
6	20	19	39
Mean per scanline	32.0	24.7	56.7
Standard deviation	12.9	5.3	14.3
Coefficient of variation	40%	21%	25%

variation in observations of high-angle fractures is about twice that of low-angle fractures. This may support the notion that fracturing, especially the more steeply dipping fractures, may vary within the project site. An alternate explanation for the greater uniformity in mapping low-angle joints is that the rather pervasive (although thin) alteration that is often present on low-angle joints aided in identifying those features.

NOTES ON FIGURES 4 THROUGH 17

Figures are provided to show in a qualitative way the results of the fracture mapping at the SFT-C. These include over 2500 joints (healed or open), shears, and faults. The scale on each figure is shown by the stationing from the shaft in hundreds of feet (e.g., Station 1+65 = 165 ft). On all figures except Fig. 4, dashed lines indicate plausible extensions of fractures, and hatched areas indicate fracture planes oriented near the orientation of the mapped rib. Identified zones illustrate closely spaced sets of fractures.

FIG. 4. Fractures at SFT-C mapping datum.

Figure 4 is a plan view of the SFT-C canister drift, heater drifts, and receiving room and shows the strike orientations of fractures identified in the field as intersecting the mapping datum. Therefore, this figure may be thought of as a horizontal slice through the SFT-C taken at the mapping datum. Since the datum is horizontal while the drift inverts rise at an 0.5% grade to the northwest, the fractures shown are closer to the floor as the observer proceeds towards the receiving room. Not all fractures mapped are shown, since not all extended to a point of intersection with the datum.

Figures 5 through 17 are compiled from sketches done by field personnel. Since many of the field sketches overlap or are locally discontinuous, the compilations reflect some degree of interpretation by the authors and do not perfectly match Fig. 4. This is particularly true with respect to the extent of the fractures; however, such interpretation is not necessarily detrimental to the work because it is based on experience with both the rock and the mapping data. Spot checks have shown that the sketch map compilations do indeed reflect the fractures present. Quantitative analysis of the fracture data will, of course, be based on the actual field-measured orientations.

Figures 5 through 8 show discontinuities mapped in the canister drift from Stations 2+00 to 4+00. These include fractures on both ribs to a height of about 10 ft and on the invert. Attempts were made to trace features from rib to invert or crown and, if possible, to the opposite rib. However, the irregular character of the excavated invert made it difficult to accurately represent this effort on the compiled sketch maps.

Figures 9 through 12 show discontinuities mapped in the heater drifts. The fractures are shown on the ribs from the floor to a height of about 8 ft; however, the floor was not exposed for mapping in either heater drift. Reference stationing in each drift was described above.

Figure 13 shows results from mapping in the receiving room (see Fig. 1 or 4 for location). The corners designated by straight lines on the drawing are actually very uneven, and the heater drift stationing does not end with identical values at these points. The canister drift is not exactly centered between the heater drifts; it is offset toward the north heater drift. This accounts for most of the 5-ft difference in heater drift rib stationing at the receiving room corners.

Figures 14 through 17 show discontinuities mapped on ribs of the instrumentation alcove, access drift, and tail drift. The instrumentation alcove is not shown on the south rib of the access drift or north rib of the

tail drift, because it had not yet been excavated when these two ribs were mapped. The instrumentation alcove centerline intersects access drift and tail drift centerlines at Stations 1+54 and 1+62, respectively.

CONCLUSIONS

Over 2500 fractures, including joints, shears, and faults, have been mapped in the drifts of the SFT-C. This was accomplished through the efforts of several individuals under constraints imposed by the project construction schedule and by the work environment. Fracture sketch maps from the field notes have been compiled into Figs. 5 through 17. The effects of possible sources of compass error have been examined in Appendix A. Considering the efforts made to minimize the compass errors in the field work, there is no reason to doubt the results of the mapping effort. The data base illustrated here by the compiled sketch maps will be analyzed and reported in a subsequent paper. This is of significance not only because of the implications for interpreting the SFT-C displacement data but also because the size of the data base allows a greater range of analyses than is possible with the more commonly available, smaller quantities of data.

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FIG. 5. Fracture sketch map, canister drift Station 2+00 to 2+50.

FIG. 7. Fracture sketch map, canister drift Station 3+00 to 3+50.

FIG. 8. Fracture sketch map, canister drift Station 3+50 to 4+00.

FIG. 9. Fracture sketch map, north heater drift (north rib).

FIG. 10. Fracture sketch map, north heater drift (south rib).

FIG. 11. Fracture sketch map, south heater drift (north rib).

FIG. 12. Fracture sketch map, south heater drift (south rib).

FIG. 13. Fracture sketch map, receiving room.

FIG. 14. Fracture sketch map, instrumentation alcove ribs.

FIG. 15. Fracture sketch map, main access drift (south rib).

FIG. 16. Fracture sketch map, tail drift (north rib).

FIG. 17. Fracture sketch map, tail drift (South)

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APPENDIX A

SOURCES OF COMPASS ERROR IN TUNNEL MAPPING

INTRODUCTION

Six sets of compass measurements were performed in drifts in the Climax stock (a quartz monzonite intrusive body) at the Nevada Test Site. The purpose of the measurements was to determine the distance at which a compass used for mapping would be affected by the proximity of various iron and steel objects. Such objects as rock bolts, steel wire mesh, mining equipment, and steel arches could draw a compass needle away from magnetic north and lead to erroneous compass readings, particularly if the compass is too close to the object. One set of measurements was made to evaluate the effect of steel arches in a previously mined drift, while five sets of measurements were made in the Spent Fuel Test--Climax (SFT-C) drifts to evaluate the other effects.

EXPERIMENTAL SETUP

In order to measure the effect of these potential sources of error, six different sets of readings were made. Three sets were in a nominal 11-ft $\times$ 11-ft (3.4 m $\times$ 3.4 m) drift, two sets were in a nominal 12-ft $\times$ 12-ft (3.7 m $\times$ 3.7 m) drift, and one set was in older, previously mined workings. For each set, a nonmetallic string was tied between opposite ribs in such a way that the string orientation was known or could be calculated. Readings were then made at 1-ft intervals along each string. These were done using a Brunton compass (note disclaimer inside front cover), such as had been used in the project fracture mapping, and corrected for a magnetic declination of N 16° E. Supplemental measurements were made in most cases at smaller intervals near each rib.

Figure A-1 shows in plan view the orientations of the three strings measured in the north heater drift of the SFT-C. Point A, common to all three strings, was a surveyor's spade set in the north rib of the drift. Point B was also a surveyor's spade, set directly across the drift from Point A. Line AB was perpendicular to the N 61° W centerline of the drift. Since the ribs were covered by steel mesh, data from Line AB showed the influence of the mesh as the measurements approached each end. Point C, where String AC was tied to the mesh on the south rib, was less than 6 in. from a rock bolt and steel bearing plate. Point D was where String AD was tied to a reinforcing bar that

FIG. A-1. Layout of lines AB, AC, and AD.

had been welded to a rock bolt. The effect of the rock bolts could be seen in the data as the readings neared Points C and D. As shown in Fig. A-1, lengths of the sides of both triangles were measured to allow calculation of the orientation of Line AC and Line AD from that of Line AB.

Figure A-2 shows in plan view the orientations of the two strings measured in the SFT-C tail drift. All four endpoints were surveyor's spads, so both Lines XY and X'Y' were perpendicular to the centerline of the tail drift. By coincidence, Line AD of the heater drift was parallel to the S 76° W tail drift centerline. Since the tail drift ribs were not covered by mesh, data from Line XY was relatively unaffected by metallic objects. Line X'Y', while clear of metallic objects at each end, passed about 6 in. from an idle drill jumbo. Data from this line illustrated the effect of large pieces of mining equipment in close proximity.

The string in the older workings was tied across the drift perpendicular to the centerline in an area supported by steel arches with timber lagging. Line JK was run from rib to rib such that the string passed within 2 in. of an arch at one end and touched the arch at the other end. The arches in this drift were 8-in.-wide-flange sections erected on 4-ft centers.

The results of measurements on Lines AB, AC, and AD are shown in Figs. A-3, A-4, and A-5, respectively. Measurements along Lines XY and X'Y' are shown in Figs. A-6 and A-7, while the measurements along Line JK are shown in Fig. A-8. In each case the measured bearing has been converted to and plotted as an azimuth. A straight line on each data plot marks the actual or true azimuth of the string. Above each data plot is a plan view illustrating the orientation of the string with respect to true north and magnetic north. Small compass dials shown on the plan views depict the variations of the compass needle with position. Adjacent features such as rock bolts, wire mesh, steel arches, and mining equipment are also included.

ANALYSIS AND DISCUSSION OF RESULTS

Many of the effects of various metallic objects can be seen by inspection of the data plots. The effects caused by wire mesh, rock bolts, a drill jumbo, and steel arches are fairly obvious. Also noticeable is that all of the readings along Line JK seem to be affected by the steel arch ground

FIG. A-2. Layout of lines XY and X'Y'.

(a) Plan view.

(b) Data plot.

FIG. A-3. Compass readings along line AB.

FIG. A-4. Compass readings along line AC.

FIG. A-5. Compass readings along line AD.

(a) Plan view.

(b) Data plot

FIG. A-6. Compass readings along line XY.

(a) Plan view.

(b) Data plot.

FIG. A-7. Compass readings along line X'Y'.

FIG. A-8. Compass readings along line JK.

support, while readings in middle portions of Lines AB, AC, AD, and XY exhibit virtually no such overall effect. Influences from steel pipes and rails on the invert about 5 ft below Line XY are also not apparent. The steel air duct and the steel cable tray along the heater-drift crown do not seem to have affected Lines AB, AC, and AD. Further, a rock bolt located diagonally about 1 ft from Point Y does not appear to have induced errors in the readings compared to Point X. Therefore, it may be deduced that most metallic objects must be in or very close to the plane of rotation of the compass needle to affect readings and that readings made within a "cage" of metal, such as steel arches, all may be suspect.

To get a better estimate of the effects of steel mesh, rock bolts, mining equipment, and steel arches, the algebraic differences between the true azimuth and the azimuths measured at points along each line were analyzed. Table A-1 lists some means and standard deviations of these differences. Two sets of means and standard deviations are shown. The first set is based on all points on a given line excepting those 1 ft or closer to the rib. The "1 ft or closer" is measured along the line, not perpendicular to the rib. The second set includes all points on the given line.

Some interesting features can be seen in the values shown in Table A-1. The means and standard deviations of the differences increased for the first three lines when all data points were included. This reflected a local influence of the rock bolts and wire mesh. Because the source of variation (the drill jumbo) was in the middle of the line rather than at one end, Line X'Y' saw a reduction in standard deviation as the endpoints were added.

TABLE A-1. Variation of measured azimuth with respect to true azimuth.

Line	Points on line over 1 ft from rib		All points on line	
	Mean difference($^{\circ}$)	Standard deviation($^{\circ}$)	Mean difference($^{\circ}$)	Standard deviation($^{\circ}$)
AB	-2.6	2.2	-5.6	5.8
AC	-1.6	5.0	5.9	22.7
AD	2.0	8.1	-6.8	27.6
XY	1.5	2.7	1.0	2.7
X'Y'	10.6	21.8	10.3	17.4
JK	34.8	24.0	13.3	41.3

Therefore, the endpoints had a correcting influence on this line as a whole. Line XY does not reflect changes as large in magnitude as any of the other lines since there was no wire mesh in the tail drift and no rock bolts or mining equipment were particularly close. As Line XY is the least variable of the five lines, it was used in comparison to the other lines for further analysis. Line JK is by contrast the most variable, reflecting both end effects from individual arches and what seems to be an overall effect from the entire series of arches. The other lines, AB, AC, and AD, seem to indicate that reliable readings can be obtained provided that the compass is kept sufficiently far away from magnetic influences.

Local effects of steel wire mesh and rock bolts were then examined. Data sets for Lines XY, AB, AC, and AD were each broken at their approximate midpoints since rock bolts occurred at some line ends but not at others. Then, as compass measurements approached the endpoints from the midpoints of each line, successive standard deviations for the new data sets were calculated. The results for the new data sets, including the measurements closest to the rib, are shown in Table A-2.

Ratios of the variances were found for each data set and recalculated to include the effects of successive readings as the endpoint of the given line segment was approached. These ratios were then compared with tabulated F values to detect variations significant at a 90% level of confidence. The variance used as a reference in the wire mesh calculations (the first four lines listed in Table A-2) was that of the "XY midpoint to Y" line. The

TABLE A-2. Deviation of compass readings for steel mesh and rock bolt influences.

Line (string) and effect	Standard deviation(^o)
AB midpoint to A, steel mesh effect	3.2
AC midpoint to A, steel mesh effect	3.1
AD midpoint to A, steel mesh effect	4.4
AB midpoint to B, steel mesh effect	7.6
AC midpoint to C, mesh and rock bolt effects	26.3
AD midpoint to D, mesh and rock bolt effects	42.6
XY midpoint to X	1.8
XY midpoint to Y	1.1

reference variance used in the rock bolt calculations was that of the opposite end of the same line, where the line approached wire mesh with no nearby rock bolts. In this manner, the proximity at which a potential error source began to affect the compass readings was identified. Using this form of analysis it was found that for a 90% level of confidence, steel wire mesh affected compass readings closer than 1 ft away and rock bolts affected readings taken closer than 1-1/2 ft away. The downturn noted on the data plots at Points A and B seems to be characteristic of the wire mesh effects as the needle tends to turn to point directly at the mesh-covered rib as the rib is approached. This deviation is slightly variable as the contour of the rib is irregular rather than plane. Where rock bolts were within about 1-1/2 ft, the needle swung to point at the bolt rather than at the mesh.

The method of analysis used to evaluate the effect of the drill jumbo was similar. However, the jumbo sat on tracks in the middle of the tail drift. No end effects were apparent from rock bolts, and no wire mesh was present on the ribs. Therefore, Lines XY and X'Y' were broken at their midpoint, and standard deviations were calculated as the readings approached the midpoint from either rib. Again, ratios of variances were found for new data sets that included successive points, this time approaching the jumbo from the ribs. At a 90% level of confidence, it was found that the compass was affected when readings were attempted closer than 2 ft from the jumbo.

Of interest is the behavior of the needle as the compass passed along a line located about 6 in. from the jumbo. The phase reversal seen in the data plot (Fig. A-7) reflects the north-pointing end of the needle staying in the north half of the compass circle. As the jumbo is passed, that end of the compass needle is deflected more and more away from magnetic north and toward the jumbo. At the centerline of the jumbo an unstable condition is reached, and the opposite end of the needle then swings around to point at the jumbo. Even disregarding the jumbo effects, Data Plot X'Y' exhibits a much larger mean difference in azimuth than do the other four plots. This seems to represent some other, more consistent source of error in the set of readings. Possibly one or both of the spads used as endpoints may have been mislocated.

The effect of individual steel arches was determined by inspection to occur when readings were made within 2 ft of an arch, as in this case. Of more importance to mapping in ground supported by steel arches, however, is what appears to be an overall "cage effect." This cage effect seemed to influence all readings made along Line JK. Other types of systematic errors,

such as those noted above for Line X'Y', seemed attributable to problems with string orientation. While these could be identified by examining the mean azimuth difference, the cage effect was more readily handled by calculating the slope of a straight line fit to the data plot.

The cage effect was evaluated by fitting a straight line to the azimuth differences for all six lines. The distance along the line was the independent variable; the azimuth difference was the dependent variable. A least squares method was employed. Except for Lines XY and X'Y', all points at least 2 ft from the line end points were used. All points were used from Line XY, and all points at least 2 ft from the jumbo were used for Line X'Y'. Table A-3 lists the magnitude of the slope of each line thus fitted.

The slopes listed in Table A-3 represent the change in measurement error (or azimuth difference) as readings proceed across the drift. A small slope corresponds to little reading change. A large slope indicates large changes in compass reading as the compass is moved across the portion of the drift containing no localized influences. The slopes are normalized by dividing by the distance actually traversed along the given line while making the readings. Line XY shows the smallest normalized slope, since it was not influenced by wire mesh or steel arches. Lines AB, AC, and AD show somewhat larger normalized slopes, possibly reflecting slight influence (or cage effect) from the heavy wire mesh. Line JK shows by far the largest normalized slope, indicating a more pronounced cage effect. This is probably due to the heavy steel arches in place. The implications for underground mapping are summarized below.

TABLE A-3. Variation of azimuth differences for gross effects.

Line (string)	Straight line fit to azimuth difference plot		
	Correlation coefficient	Slope	Normalized slope
AB	0.81	0.76	0.10
AC	0.95	1.22	0.14
AD	0.97	2.10	0.15
XY	0.79	0.45	0.03
X'Y'	0.91	0.49	-
JK	0.96	7.93	1.32

CONCLUSIONS

Several conclusions may be drawn for geologic mapping with a magnetic compass. These summarize the potential for compass error induced by wire mesh, rock bolts, and mining equipment. First, most small metallic objects, including rock bolts, should not affect compass readings if located above or below the plane of rotation of the compass needle. Second, steel wire mesh on rock surfaces usually affects compass readings only if the compass is closer than 1 ft to the mesh. Third, rock bolts near or in the plane of the compass needle generally affect readings taken less than 1-1/2 ft away. Fourth, large pieces of mining equipment affect readings made within 2 ft.

Although the field work described herein was performed in granite tunnels, the results should be applicable to field work in surface excavations as well. These conclusions cannot apply, however, to mapping in underground excavations supported by steel arches. The effect of these arches appears to be pervasive, almost preventing any underground mapping work that depends on a magnetic north reference. Only one case has been considered here; therefore, this caution might not apply equally in tunnels having larger dimensions, lighter weight arches, or larger arch spacings. Other situations not addressed here and requiring further consideration might include effects of direct current power lines and of certain types of mineralization. These latter effects were not a problem in the geologic mapping that was associated with these trial measurements; therefore, they were not considered.