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INELASTIC DEFORMATIONS OF FAULT AND SHEAR ZONES IN GRANITIC ROCK

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ABSTRACT

Deformations during heating and cooling of three drifts in granitic rock were influenced by the presence of faults and shear zones. Thermal deformations were significantly larger in sheared and faulted zones than where the rock was jointed, but neither sheared nor faulted. Furthermore, thermal deformations in faulted or sheared rock were not significantly recovered during subsequent cooling, thus a permanent deformation remained. This inelastic response is in contrast with elastic behavior identified in unfaulted and unsheared rock segments. A companion paper (Butkovich and Patrick, 1986a) indicates that deformations in unsheared or unfaulted rock were effectively modeled as an elastic response.

We conclude that permanent deformations occurred in fractures with crushed minerals and fracture filling or gouge materials. Potential mechanisms for this permanent deformation are asperity re-adjustments during thermal deformations, micro-shearing, asperity crushing and crushing of the secondary fracture filling minerals. Additionally, modulus differences in sheared or faulted rock as compared to more intact rock would result in greater deformations in response to the same thermal loads.

INTRODUCTION

This paper reports results of convergence monitoring of three parallel drifts approximately 425 m below surface in quartz monzonite. The work was performed within the Climax Stock (located in the Nevada Test Site) as part of the Spent Fuel Test-Climax. Facilities consisted of three parallel drifts with heaters in the outer drifts and a combination of electrical simulators and spent fuel canisters in the central drift.

As part of an overall geotechnical monitoring program, wire extensometers were installed at five

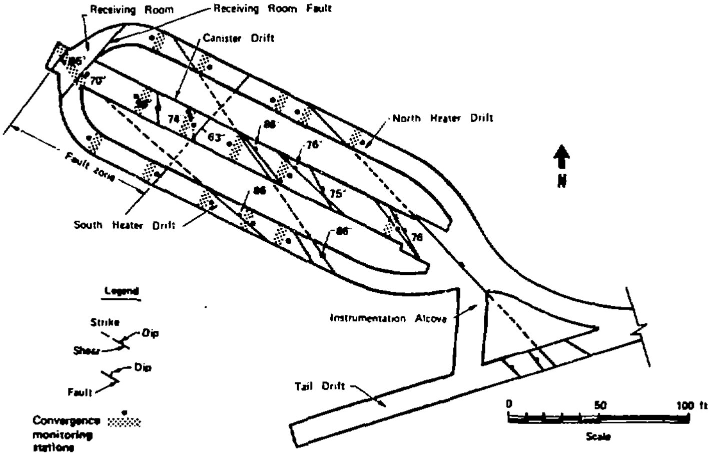

Fig. 1. Location of convergence monitoring stations.

*Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

measurement stations in each heater drift and six stations in the canister drift to measure both horizontal and vertical drift convergence (Fig. 1). Locations of measurement stations were chosen to monitor end effects and the effects of fracturing. A three-year heated phase and a six-month cooldown period were monitored. The data reported here were collected on a continual basis by a computer data acquisition system.

Early analysis of convergence included data from tape extensometers which measured the same points as were monitored by the convergence wire extensometers (CWEs). These data were not continuous, and in order to compare the results with finite-element (FE) modeling, the data from all stations within each drift were averaged together. These comparisons, as discussed in previous reports (Yow and Butkovich, 1982; Butkovich et al. 1982, Patrick et al. 1982; and Butkovich and Patrick, 1986b), indicate that there is general agreement between trends evident in the convergence measurements and in the FE model calculations. However, since the data were averaged, any differences due to local structure would be masked. With the continuous data from the CWEs, a more detailed analyses can be made of the influence of individual geologic structures.

DISCUSSION

The first comparisons that were made are shown on Figures 2 and 3, which give generalized curves of tape extensometer data, CWE data and FE model calculations for the Canister Drift. In general, the tape, CWE data, and FE models all indicate similar trends (curve shapes are similar). This supports earlier conclusions that in general the rock mass behaved elastically. The fact that the measured and calculated magnitudes do not match well for horizontal convergence (Fig. 2) is of less significance since calculated magnitudes are dependent on the moduli assumed. The three calculations shown are the same except for the moduli assumed, therefore, a modulus assumption between those of calculations 2 and 3 should provide a good match with measurements. However, any modulus assumptions other than those for calculation 2 would adversely effect the current good match for the vertical data (Fig. 3). This points out an important difference in vertical and horizontal convergence response which will be discussed later.

As was indicated earlier, these comparisons between measured and calculated drift closures used averaged tape readings from each station within a given drift. The convergence wire data were analyzed to determine whether the data are independent of geologic structure. Figure 4 shows the maximum vertical deformations (from before fuel emplacement until just prior to fuel removal) in each drift. The deformations are referenced to equivalent stationing within the Canister Drift. As can be seen, the measurements are quite constant with station except for the stations near the far end of the drifts near the receiving room where there is a fault. Figure 5 shows the data from the horizontal CWEs. These data have considerably more variation than the vertical data, especially in the heater drifts. The variation is not well understood at this time; however, there is an increase in magnitude in the area of the fault in the North Heater Drift which is similar to that seen in vertical measurements. In contrast, the canister drift data are fairly uniform. Magnitudes decrease near the beginning of the fault zone. The apparent increase across the fault (last measurement) is misleading since this is a much longer measurement section than the drift cross-sections measured at all other stations, and it is not perpendicular to the drift. Therefore, the data actually indicate less horizontal thermal deformation in the fault zone than in the remainder of the Canister Drift.

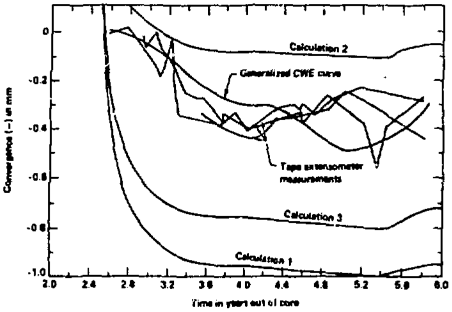

Fig. 2. Average canister drift horizontal convergence.

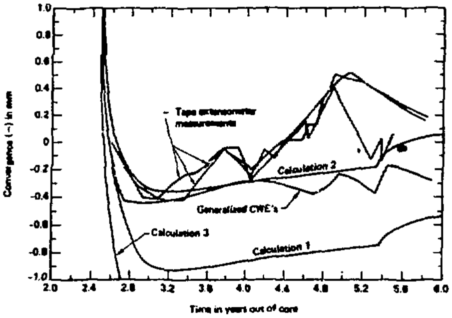

Fig. 3. Average canister drift vertical convergence.

Figures 6 and 7 show the cooldown cycle data. No particular station related trend is apparent in the data, i.e., no station has a clearly different response than any other station. This is in contrast to the thermal phase data, where stations at the ends of the drifts were clearly different in response from the remaining stations. This would indicate that opening of the fault as the rock cooled was not fundamentally different than the contraction of the unfaulted rock mass in general.

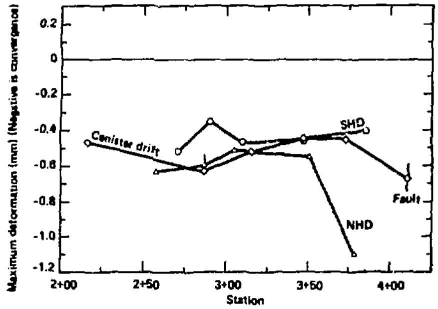

Fig. 4. Thermal phase vertical drift deformations.

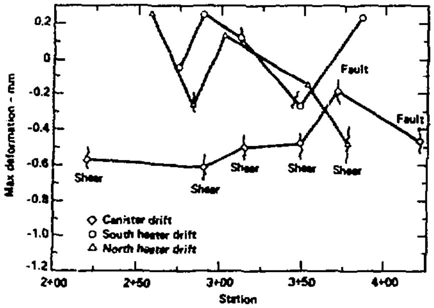

Fig. 5. Thermal phase horizontal drift convergence.

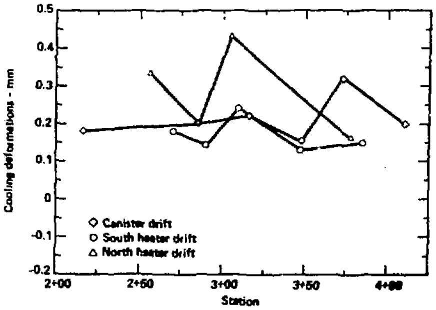

Fig. 6. Cooldown phase vertical drift convergence.

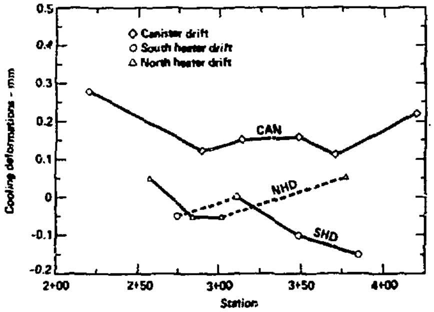

Fig. 7. Cooldown phase horizontal drift convergence.

Two factors, however, should be considered. First, the ends of drifts (where the fault was located) should have seen less deformation response since the thermal loads were smaller. Therefore, responses of the same magnitude in these areas as seen elsewhere in the drifts actually indicate greater displacements for the same change in rock temperature. This may reflect a lower modulus (E) for faulted rock than intact rock, since $\epsilon = \sigma/E$. This would be expected in the highly broken and altered rock associated with the fault. The second factor to consider is that the cooling was incomplete at the time that the monitoring ceased. The importance of this is apparent when mechanisms of fracture behavior are considered. It is likely that during the early portions of the heating phase the fractures closed at a more rapid rate than the intact rock expanded, but that as the fractures closed, they responded increasingly as intact rock. Thus the overall deformations monitored in the faulted rock would always be greater than that monitored in intact rock, consisting of early fracture closure which was greater than rock expansion plus the later deformations which were similar to (depending on the equivalent modulus once the fracture closed) the intact rock expansion from the time of fracture closure. As cooling started, the initial response would be similar to intact rock since the fractures had not yet opened and would be contrasted to the elastic response only when the cooling had progressed sufficiently to allow the fractures to open up. This process can not be fully evaluated since the monitoring ceased before the cooling was complete. It is merely identified as a process that needs to be considered, which seems consistent with the observations made in the North Heater drift. During the early heating phase (see Fig. 8), divergence between the monitored convergence at the fault and that monitored elsewhere in this drift was increasing with time. However, approximately one year before cooldown started the curve became parallel to the other curves.

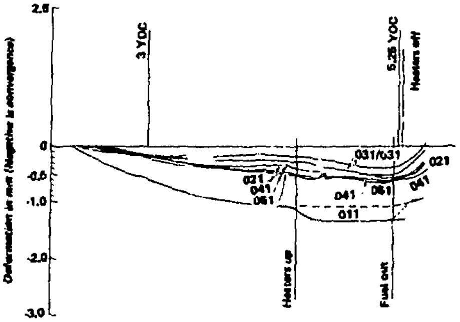

Fig. 8. Vertical deformation of north heater drift.

There appears to be a slight overall increase in cooling deformation towards the far end of the canister drift (station 4+00), whereas the north heater drift appears to have a significant decrease in cooling deformation towards the fault. The station nearby the fault has the smallest amount of cooling deformations and the smallest maximum deformations. A similar increase is noted in the vertical (but not horizontal) CWEs of the south heater drift. No continuum mechanism, which does not account for differing moduli, has been identified that explains the greater amount of cooling deformations at specific measurement stations. The smaller percent recoveries are usually associated with the location of shear or fault zones. Since the converse is not always true, this observation may merely be coincidental.

It is interesting to note that both horizontal and vertical responses during heating and cooling are consistent at each measurement point, i.e., both increase or decrease in the same fashion. This consistency is indicated on Figures 7 and 10, which show very similar patterns of influence for both vertical and horizontal extensometers. This leads to the observation that whatever influenced the vertical extensometer also influenced the horizontal extensometer at each measurement station in a similar manner.

With ventilation proceeding from the rail car room towards the receiving room, the greatest amount of recovery during cooldown for any given time should conceptually be in the sections or stations nearest the rail car room. This would seem true because of warming of the ventilation air as it flows towards the receiving room. This conceptual model is applicable only if the air flow is uniform laminar flow. However, we know that temperature varied by ≥ 2-3°C from point to point within the canister drift. This implies that large convection cells may have been operating in the drifts so as to "even out" heat transfer from the rock to the air.

There is a fairly constant ratio of cooldown/thermal deformations (amount of recovery) in most of the canister drift. However, the ratios of recoveries change dramatically (large increase in recovery) at Station 3+75. This may be related to structure since this is the area where the fault zone and shear zones begin to intersect. The increase in recovery near the receiving room is not easily explained unless it was influenced by structure. The implications of structural control would be that fractures in this area should be opening more than those elsewhere in the drifts. Therefore, if the concept is valid that fractures respond as intact rock until a certain level of cooldown is experienced, this would be the most appropriate place to look for differences in cooldown response. As noted on Fig. 6, there is an increase in magnitude of vertical convergence at this station relative to other stations in the canister drift. It is interesting that similar observations can be made at station 3+00 in the north heater drift. However, at both of these places the horizontal response does not show any similar behavior.

Note that at the CWE array in the north heater drift at Station 2+85, which spans a shear zone, there is a drop in the deformation ratio between cooling and heating. Also, there is a definite drop in magnitude of the maximum deformations at this station observed by the horizontal CWE. The decrease, if any, for the vertical CWE is very subtle. The locations of shear zones are shown on the percent recovery curves (Fig. 9). It appears that there is a reduction in the percentage recovery and an increase in magnitude of deformation due to the presence of shear zones.

Because the behavior is not entirely consistent, it is important to recognize how the orientation of geologic fractures would influence individual CWEs. The shear zones are essentially vertical or very steeply dipping features. As a result, vertical wire extensometers would not be able to measure permanent compression of the infilling minerals of a shear zone; rather, they would monitor deformations of the infilling of low

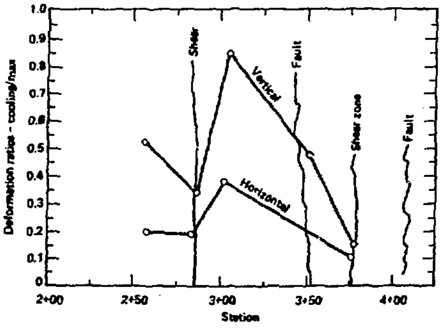

Fig. 9. Ratio of cooling/heating deformation in the north heater drift.

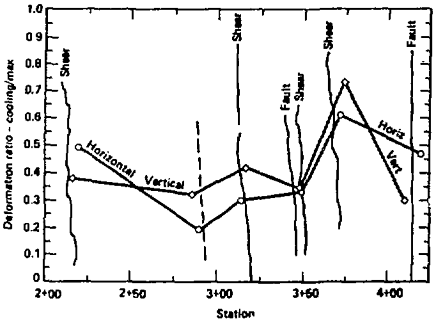

Fig. 10. Ratio of cooling/heating deformations in canister drift.

angle joints. Vertical extensometers could only monitor the influence of vertical shear zones as spatial differences in cumulative permanent deformations of the pervasive low angle joints, or as the result of lower modulus associated with the shear zones. This could result from microcracking being more prevalent near intersections of low angle joints and shear zones than along low angle joints without shears. This mechanism was also indicated by data from rod extensometers, but that is beyond the scope of this paper. In contrast, the horizontal CWEs would be able to measure permanent deformation of the steeply dipping shear zones and vertical (open) fractures, but could measure only a small component of permanent deformation of low angle joints. Unless the same microcracking phenomenon was able to take place on the shear zones as on the low angle joints, there should not be the strong correlation of recovery between vertical and horizontal CWEs that is shown on the curves. This leads to the conclusion that lower modulus associated with shear zones was the mechanism for the differences. This seems plausible since a lower modulus would be expected at these more highly altered and fractured locations.

CONCLUSIONS

Analyses of convergence data from three drifts in fractured granitic rock indicate that the convergence of the drifts during heating of the rock was perturbed by the presence of faults (or shears). Convergence during heating was much larger in faulted rock than in intact rock. Significant changes were noted at the ends of the drifts where a fault was located. This was true even though the thermal loading was less in the area of the fault. At one station near the fault the convergence rate during the entire three years of monitoring was consistently double that of the overall drift convergence. Monitoring during six months of cooldown of the rock showed smaller differences in the convergence of faulted rock in comparison to unfaulted rock. Because the cooldown was not complete at the end of the monitoring, it is concluded that fractures which had closed during heating had not opened sufficiently to respond differently than the intact rock at the end of the monitoring period. This is supported by observations at a couple of monitoring stations where the percentage recovery of thermal convergence was greater. At these points the magnitude of cooldown displacements were greater than at other places in the drifts. It is also supported by the observation that near the fault, in one of the heater drifts, the convergence during heating of the rock was continuing at about double the rate of the rest of the drift. However, about a year before cooldown the convergence rate asymptotically approached that in the overall drift. This possibly indicates that the fault was closed sufficiently at that point to respond similarly to intact rock. Further evidence of the influence of the fault was a very strong correlation between the amount of recovered thermal deformations in both the vertical and horizontal sections. There is a one to one correlation in the change of vertical and horizontal recovery at each monitoring station. This indicates that the same mechanism was seen by both vertical and horizontal measurements. However, the geologic structure would not be monitored equally in both directions. Therefore, a lower modulus associated with alteration and fracturing in the fault and shear zones is identified as the most likely cause of the structural influence on convergence.

These observations lead to the following conclusions. First, convergence differences during heating that were related to the presence of a fault are probably caused by differences in the modulus of the intact rock compared to that of the altered and fractured rock. Because the fractured rock would have a lower modulus, it would experience larger deformations for the same loading or boundary conditions. Secondly, it appears that after fractures close sufficiently the rock containing them responds similarly to intact rock. This was seen during both heating and early cooling. Finally, a portion of the thermally induced closure of the fractures was not recovered during more complete cooldown of the rock. Thus a permanent deformation can be caused by closure of fractures.

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