FINAL REPORT

Effects of Slip Velocity and Temperature on the Friction of Rocks in Earthquake Zones

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1.0 Abstract

The purpose of this work was to investigate the frictional properties of several important rocks and minerals that comprise the Earth's crust under various combination of sliding speed, normal force, and temperature. The research test plan was to perform tests using two types of existing friction testing apparatus located at Oak Ridge National Laboratory (ORNL): a pin-on-disk (POD) apparatus and the sub-scale brake testing (SSBT) apparatus. The goal of these tests was to measure the kinetic friction coefficient of various material combinations as a function of sliding velocity. Brown University was responsible for supplying test specimens in the size and shape needed to fit ORNL's apparatus. During the course of the work, based on initial POD results, and the non-availability of appropriate samples to test using the standard SSBT apparatus configuration, a mutual decision was made by Brown University and ORNL principal investigators to concentrate the work exclusively on the POD experiments. A total of 32 friction experiments were conducted at room temperature and at 500^{o} C, in air, on various sliding couples of olivine, quartzite, diabase, and calcite. Sliding speeds of 0.01 to 0.95 m/s were used under normal forces of either 10 or 30 N. Detailed friction data were obtained as a function of time, and the surfaces of representative test specimens were photographed under an optical microscope. The contact conditions used in this work produced significant sliding wear, with surface fracture and debris generation. The effects of sliding wear on friction were significant, and produced test-to-test variabilities in friction data. Project funding limitations did not enable us to explore the sources of the data scatter, as related to the effects of specimen preparation, specimen heterogeneity, and the repeatability of trends needed for a suitable journal publication. Plans are to continue this work in the coming year to improve the repeatability of the data, and to enable trends in rock-on-rock frictional behavior to be better understood.

2.0 Introduction and Background (from D. Goldsby, Brown Univesity)

"A mini-revolution in the field of earthquake physics in the last decade has revealed that the frictional properties of rocks at high slip velocities (~1 m/s) during an earthquake are very different from those at low, quasi-static slip rates. In particular, a host of studies have shown that very low frictional strengths of rocks at earthquake slip rates appear to be the rule rather than the exception. Such low values of friction, and the nature of fault strength recovery after an earthquake, have enormous implications for the earthquake cycle – from determining whether earthquake ruptures propagate as cracks or slip pulses, to constraining the magnitudes of strong ground motions and shaking. Understanding the frictional properties of rocks at dynamic slip rates is a critical component of earthquake physics.

The study of frictional properties of engineering materials at high sliding speeds is common, and tribologists have devised and employed numerous advanced techniques and apparatus for conducting such experiments. The study of the frictional properties of rocks at high slip rates is, in comparison, in its infancy, and rock mechanicians therefore lack the appropriate experimental apparatus to perform such tests."

Owing to its range of friction and wear testing capabilities, Oak Ridge National Laboratory was asked to support a portion of the work led by Brown University. This involved friction testing a limited selection of rocks and minerals in two of its existing instruments. This report summarizes approximately 0.02 person years of ORNL testing support, and therefore should not be considered a definitive study, but rather a preliminary study of selected material combinations under limited testing conditions and with a limited number of repeated trials.

3.0 Friction Test Procedure

Two test configurations were originally considered: a pin sliding on the face of a disk, and a flat block sliding against a larger disk on a device originally designed to test automotive and truck brake materials. The latter is referred to as a Sub-Scale Brake Materials Tester (SSBT). During the course of this work, it was determined that the SSBT would present significant set-up an specimen preparation difficulties that would limit the number of experiments that could be performed under the current budget allocation. Therefore, all testing reported here was conducted using the pin on disk (POD) tester. The friction coefficient is defined here as the ratio of the tangential force to the normal force during sliding contact.

The POD configuration used a cylindrical (9.53 mm dia. x 25 mm long) round-ended pin, sliding against the face of a rotating 40 mm diameter disk specimen. The machine was built by AMTI, Massachusetts in 1987 under subcontract to ORNL. It has the ability to test sliding friction and wear at temperatures from ambient to 1000^{o} C. The diameter of the circular track for all tests was fixed at 19.0 mm. An adapter was designed and machined to hold upper (pin) specimens that were provided by Brown University. Pin and disk specimens were tested 'as-received.' Except for the first four experiments, they were tested in the self-mated (like-on-like) condition. We did not attempt to clean pins or disks in solvents or water-based cleaners prior to testing because several of the specimen surfaces were cracked and we were concerned that liquids would penetrate the specimens to affect their friction and wear characteristics.

During the first four tests, the load and total sliding distance were kept constant at 10 N and 5 m, respectively. Data for these initial tests were digitally recorded at 100/s for intervals of 4 seconds with a gap of 1 second prior to the next data sample. Thus for a test of 1 min 40 s duration, there were 20 intervals. Only four initial tests were run due to excessive wear on the olivine slider. The contact stress for the slider at the end of the experiment was estimated at 2.05 MPa, based on the worn area on the slider tip. After the first four scoping runs, subsequent tests were conducted at normal force of 30 N and for short sliding durations.

Specimens of four different geological materials were supplied by D. Goldsby of Brown University: olivine, quartzite, diabase, and calcite. Original plans called for testing all materials at room temperature and 500 °C, but since calcite decomposes at the higher temperature, its test temperature was reduced to 300 °C.

Table 1 presents the list of experiments and their testing identification numbers. The code numbers used were BrUn-XXX, where XXX was the chronological sequence of the experiments. The data have been sorted to group materials by test temperature, specimen material, and sliding speed. To investigate static friction effects, some tests began with the load applied, but in other cases, the disk was set in motion first, and the slider (pin) was lowered and raised before the test ended. In certain cases (Tests BrUN20 and BrUn21) had to prematurely terminated due either to problems with specimen fracture or deterioration (calcite run at 500 °C).

Table 1. Conditions for Pin-on-Disk Tests

TEST ID BrUn or BU_	Slider Material	Flat Material	System temp (C)	Humidity (%RH)	Load (N)	Speed (m/s)	Load * Method	Sliding dist (m or time)
1	olivine	quartzite	21	48	10	0.05	L	5
2	olivine	olivine	21	48	10	0.05	L	5
4	olivine	quartzite	21	48	10	0.5	L	5
6	olivine	olivine	21	48	10	0.5	L	5
30	calcite	calcite	21	29	30	0.01	L	5 sec
31	calcite	calcite	21	29	30	0.3	DL	5 sec
13	calcite	calcite	21	48	30	0.95	L	< 1 m
13a	calcite	calcite	21	48	30	0.95	L	~ 1
32	diabase	diabase	21	29	30	0.01	L	5 sec
33	diabase	diabase	21	29	30	0.3	DL	5 sec
12	diabase	diabase	21	48	30	0.95	L	1
25	olivine	olivine	21	30	30	0.01	L	5 sec
28	olivine	olivine	21	30	30	0.01	L	5 sec
29	olivine	olivine	21	30	30	0.3	DL	5 sec
14	olivine	olivine	21	48	30	0.95	L	~ 1
23	quartzite	quartzite	21	30	30	0.01	L	5 sec
10	quartzite	quartzite	21	48	30	0.05	L	1
15	quartzite	quartzite	21	33	30	0.3	DU	5 sec
16	quartzite	quartzite	21	33	30	0.3	DU	5 sec
17	quartzite	quartzite	21	33	30	0.3	DU	5 sec
11	quartzite	quartzite	21	48	30	0.95	L	1
24	quartzite	quartzite	21	30	30	0.95	D	~ 95 m
22	calcite	calcite	300	33	30	0.3	DU	5 sec
21	calcite	calcite	500	31	30	0.3	n/a	aborted
20	diabase	diabase	500	31	30	0.3	DU	rejected
20b	diabase	diabase	500	31	30	0.3	DU	5 sec
26	olivine	olivine	500	30	30	0.01	D	5 sec
34	olivine	olivine	500	29	30	0.01	L	5 sec
27	olivine	olivine	500	30	30	0.3	DL	5 sec
35	olivine	olivine	500	29	30	0.3	DL	5 sec
18	quartzite	quartzite	500	33	30	0.3	DU	5 sec
19	quartzite	quartzite	500	33	30	0.3	DU	5 sec

* L = start motor with specimen under load;   DU = set down the pin then lift it up as the disk is rotating at full speed
D = set down the pin after rotation starts and leave it down until test is over

4.0 Results and Discussion

4.1 *Scoping tests*. As shown in Table 1, initial 'scoping' tests were conducted at two speeds (0.05 and 0.5 m/s) and with two couples (self-mated olivine and olivine on quartzite for 5 m sliding distance. Figure 1 summarizes the results of these tests. At the lower speed, the friction coefficient for self-mated olivine seemed to be more stable than that for olivine on quartzite which rose with time. If sliding distance, rather than time, were plotted, after 5 m, the friction coefficient for olivine on quartzite would be about the same for both speeds, but that for self-mated olivine after 5 m is slightly less for the lower speed run.

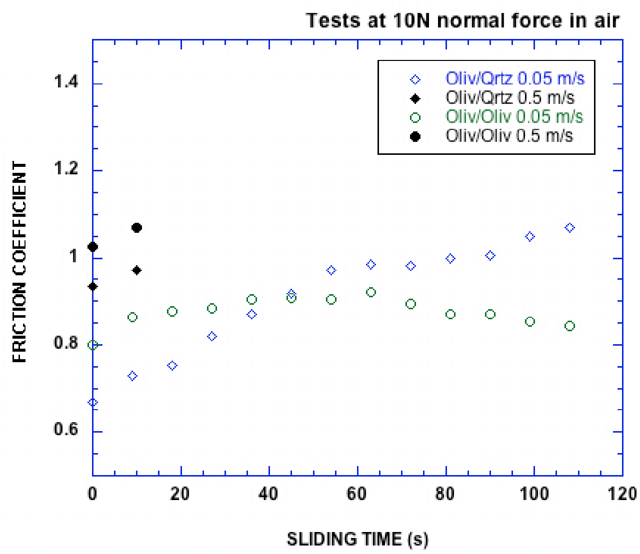


Figure 1. Plots of friction coefficient versus time for BrUn01, 02, 04, and 06.

4.2 *Surface Finish Effects*. The effects of initial disk surface finish of the friction of quartzite sliding at 30 N and 0.3 m/s in room temperature air are shown in Figure 2 for tests in which the motor was started, then the slider lowered and raised again. The data capture rate was 1000/s. The 100 and 400 grit finishes provided lower friction than the coarser 24 grit finish. The use of more highly-polished specimens is suggested because fractures and pits remaining from coarser grade specimen polishing can lead to wear debris which can directly affect the frictional stability and transitions to severe abrasive wear conditions.

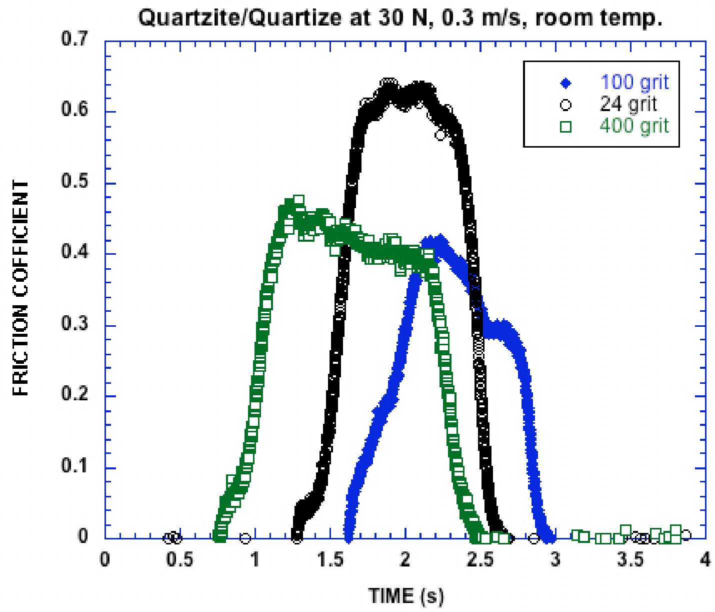


Figure 2. Effects of initial disk surface finish on friction coefficient (BrUn15, -16, -17).

4.3 *Comparisons of Frictional Behavior at Different Speeds*.

The maximum friction coefficient measured at anytime during each room temperature run, and at each speed, is given in Table 2. These maxima may have occurred at different sliding times or sliding distances for each material combination, but the general trend for all minerals is for the maximum friction coefficient to decrease with increasing sliding speed. In general, quartzite couples tended to have lower friction than the other materials, but this was not always true.

Table 2. Maximum Sliding Friction Coefficients for Each Speed (room temperature)

Pin/Disk	0.01 m/s	0.30 m/s	0.95 m/s
Olivine/Olivine	0.75	0.66	0.57
Quartzite/Quartzite	0.68	0.42	0.49
Diabase/Diabase	0.82	0.63	0.47
Calcite/Calcite	0.80	0.63	0.54

4.4 *Comparison of Frictional Behavior at Different Temperatures*

Replicate runs were performed at elevated temperatures (except for calcite, which was to be tested twice at 500 ^{o}C, but due to thermal decomposition, the mineral was only tested once, at 300 ^{o}C). All elevated temperature tests were run at 30 N load and 0.30 m/s sliding speed for approximately 5 s, except for two runs on olivine at 0.01 m/s. The maximum recorded friction coefficients during each of the runs is shown in Table 3. Olivine friction was affected by speed at elevated temperature. The higher speeds produced lower friction.

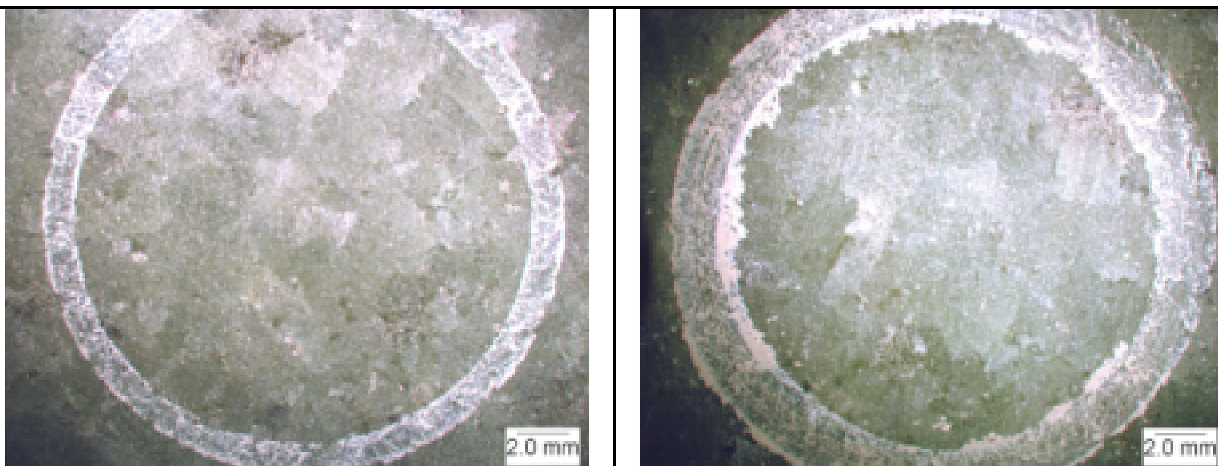
Table 3. Maximum Sliding Friction Coefficients for Elevated Temperature Runs

Pin/Disk	Speed (m/s)	Temperature (^{o}C)	First Run (Run ID)	Second Run (Run ID)
Olivine/Olivine	0.01	500	0.83 (26)	0.75 (34)
Olivine/Olivine	0.30	500	0.46 (27)	0.49 (35)
Quartzite/Quartzite	0.30	500	0.60 (18)	0.52 (19)
Diabase/Diabase	0.30	500	0.59 (20b)	*
Calcite/Calcite	0.30	300	0.51 (22)	*

* replicate run terminated prematurely

4.5 *Role of Wear in Frictional Behavior*.

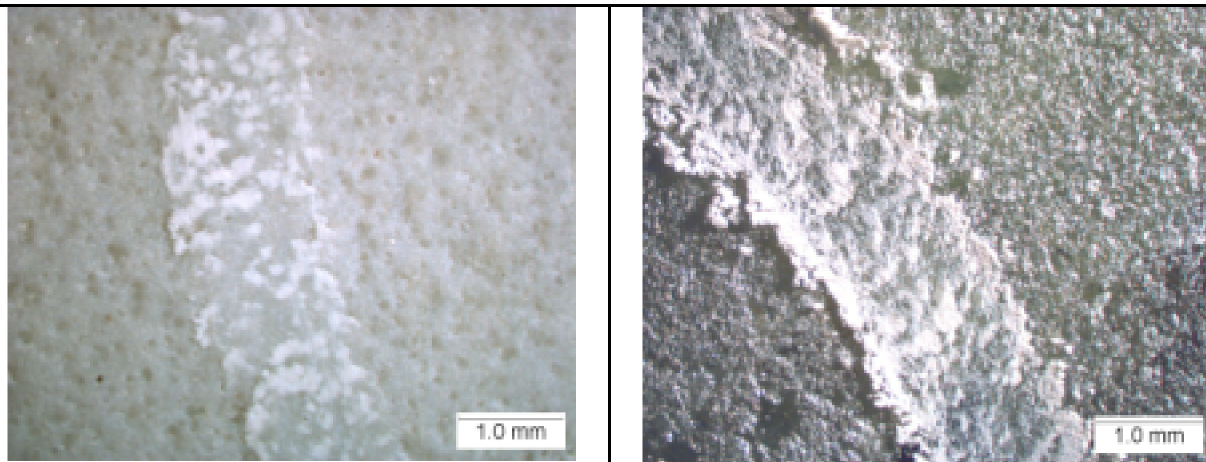
It is well established that the presence of wear particles can affect friction, and the sooner wear begins to occur, the sooner, the effects of these third-bodies will be observed in the friction-time trace. Figures 3 and 4, below show wear tracks on olivine disks indicating the white powdery debris that was produced during the sliding experiments. Similarly, Figure 5 shows a slider tip before and after the wear debris was removed. The area of the oval wear mark on the slider, by image analysis, was 4,878,688 mm^2.



Wear track for test BrUn02 showing wear debris (not cleaned off)

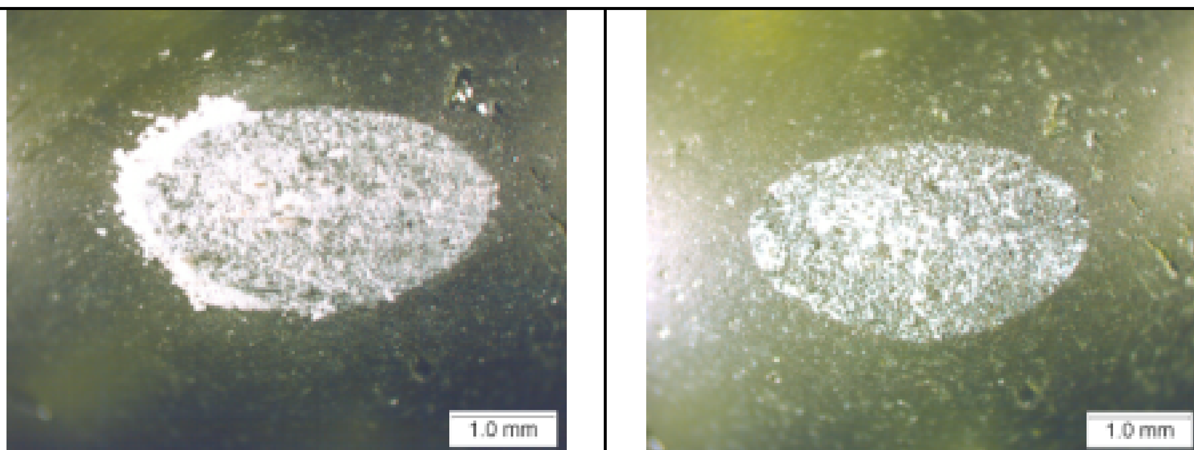
Wear track for test BrUn06 showing a wider track probably due to tip wear (debris left as-is)

Figure 3. Circular wear tracks on disk specimens of olivine showing debris accumulations as well as particles that were pushed to the side of the sliding path.



Close-up of disk wear track for BrUn01 showing accumulated debris	Close-up of the disk wear track for BrUn02 showing accumulated debris

Figure 4. Higher magnification optical microscope images of wear debris build-ups on quartzite (left) and olivine (right).



Worn olivine slider tip after completing the first series of tests (debris in place)	Worn olivine slider tip after completing the first series of tests (debris removed)

Figure 5. Tip of a worn olivine slider before (left) and after (right) wer debris removal.

5.0 Summary and Recommendations

A series of pin-on-disk sliding friction experiments were conducted in air using various combinations of rocks and minerals, most of them self-mated. Speeds varied from 0.01 to 0.95 m/s and loads ranged from 10 to 30 N. In summary,

a) Friction coefficients ranged from about 0.4 to over 1.0. Most experiments were of short duration to study initial stages of sliding contact. Often friction coefficients did not reach a steady-state value (varied with time) and only the maximum value recorded during eacg experiment was reported.

b) Initial surface preparation of the brittle specimens seemed to leave the test surfaces pre-fractured, and under the contact stresses from the slider tip, resulted in a rapid transition to 2- and 3-body abrasive wear that contributed to high, irregular, and non-repeatable friction results. It is recommended that carefully-polished specimens be used in future studies.

c) Calcite could not be tested at 500 ^{o}C like the other specimens due to the thermal decomposition of the samples, and testing temperature was reduced to 300 ^{o}C.

d) Limited specimens of each material were available and that limited the number of replicate tests. In some cases, there was only one experiment possible per test condition and results were not felt to be definitive. Regrinding of disk surfaces or pin tips was not practical in most cases due to the extent of the damage due to wear.

e) Subject to the foregoing limitations: (i) initial surface preparation affected friction, (ii) the quartzite/quartzite couple seemed to have lowest maximum friction coefficient at room temperature, (iii) the olivine/olivine couple had the lowest maximum friction coefficient at 500 ^{o}C.

Further research, with better-prepared test specimens and more replicate experiments, is needed to verify the trends and findings reported here. Also, the question of whether a pin-on-disk type of experiment adequately simulates buried interfaces in earthquake zones remains to be resolved. Issues bearing on the latter are: the ability of a POD to produce the confined, high hydrostatic stress field in the interface needed to induce ductility in otherwise brittle rocks and minerals, whether the shear rate is high enough, and whether the motion and presence of third-body particles (wear debris) is adequately simulated.

6.0 Publications

In consideration of the preliminary nature of these results, and the need to replicate and expand upon these experiments to verify trends and improve data repeatability, no publications resulted from this work.