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Friction Level of Faults During Large Earthquakes

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Synopsis

Temperature measurements were used to estimate the level of fault friction of large earthquakes. These observations were made in boreholes drilled into fault-zones following large earthquakes in Taiwan, China and Japan. From the temperatures, we are able to estimate the heat generated at the time of the earthquake and thus the level of friction on the fault. The results for all three earthquakes show that the coefficient of friction during the earthquake was 0.1 or less. This is much smaller than values for rock friction measured in the laboratory. The friction determined from rock mechanics experiments represents static friction values, while the temperature measurement values are the dynamic friction during large slip of earthquakes. So static friction of rocks is much higher than the dynamic friction during large earthquake slip.

Keywords: Earthquake, Fault, Friction, Temperature, Chi-Chi, Wenchuan, Tohoku-oki

1. Research Career

First is a summary of my research career. I received a PhD degree in geophysics at Columbia Univ. in 1984 and then held three positions: Seismologist, Rabaul Volcano Observatory, Papua New Guinea (1984-1988), Research Scientist, US Geological Survey in Pasadena, California (1984-1999) and Prof., Disaster Prevention Research Institute, Kyoto Univ. (1999-2022). I lived 3 years in Papua New Guinea, 11 years in the US and 23 years in Japan, however, in terms of research ideas, first author papers and remembered experiences, the durations of the three periods seem similar in my mind. In geophysics sometimes 'apparent time' is used, which measures time by counting significant events. The apparent time for my three positions seems about the same despite the large differences in the actual time (Fig. 1). The total numbers of published papers is more closely related to the actual time, since that depends more on daily activities and collaborations with other researchers.

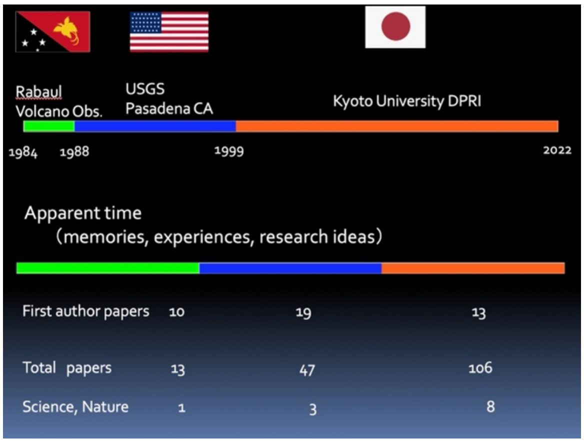


Fig. 1. Summary of my three career positions. Top colored line is actual time. Bottom line is 'apparent' time.

1.1 Rabaul Volcano Obs. 1984-1988

My first job at the Volcano Observatory of the Papua New Guinea Geological Survey was an exciting time. I observed eruptions at 4 different volcanoes and felt the shaking from 4 M7 earthquakes. Also there was very strong seismic and

Fig. 2. Some photos of eruptions in Papua New Guinea. 1985 Langila (left). 1985 Uluwan (center). 1986 Manam (right).

ground deformation activity in Rabaul caldera. No eruption occurred in Rabaul at that time, but a large eruption later in 1994 destroyed the town.

1.2 US Geological Survey 1988-1999

I returned to the US in 1988 and worked for 11 years at the US Geological Survey (USGS) on the Caltech campus in Pasadena, California. Providing public information about earthquakes to the many people in the Los Angeles region was very different from sparsely populated Papua Guinea. Even a small earthquake that was felt by people was a TV news story. I was interviewed over 100 times on TV and radio about earthquakes while working at the USGS. Two large earthquakes, 1992 Landers earthquake (Mw7.3) and 1994 Northridge earthquake (Mw6.7) were important events. The two earthquakes caused considerable damage and were the focus of much research. There were considerable efforts to use the USGS research results to help recovery and provide seismic hazard information for the public. In 1992, I was a member of the Volcano Crisis Assistance Team that monitored and provided information on the large eruption of Mt. Pinatubo in the Philippines.

Fig. 3. Caltech-USGS press room is busy after an earthquake in Los Angeles.

1.3 DPRI Kyoto University

In 1999 I came to Japan to become a professor at the Disaster Prevention Research Institute (DPRI) of Kyoto University. Working at DPRI, teaching classes in Japanese and English and living in Japan, were all new experiences for me.

Soon after arriving in Japan, the Chi-Chi earthquake (Mw7.7) occurred in Taiwan. With DPRI colleagues we went to investigate the large surface faulting and damage caused by the earthquake. This was the beginning of my interest in this earthquake and borehole drilling into faults to make temperature measurements for estimating fault friction.

2. Fault-zone drilling and Measurements of Fault Friction

Estimating and understanding the level of friction during the faulting of large earthquakes has been an active topic of research for decades in seismology. There have been many debates about whether the level of fault stress is high (~100 MPa) or low (~1 MPa) during earthquakes. In laboratory experiments the coefficient of friction for rocks has been measure in the range of 0.6 to 0.7 (Byerlee, 1978) which would indicate high stress. If the friction is this high, large amount of heat would be produced during earthquakes and the slip during earthquakes would produce temperatures high enough to melt the rocks. However, for the San Andreas fault, the measured values of heat flow are relatively low, much lower than what would be expected for a coefficient of friction of 0.6 to 0.7.

Also melted rocks (pseudotachylytes) are very rare along the fault. This is called the San Andreas Heat Paradox (e.g. Lachenbruch and Sass, 1980). There have been discussions about whether or not the laboratory friction values are representative of natural faults, and if the heat flow measurements accurately reflect the frictional heat on the fault.

We realized that one of the most direct ways to study this problem was to measure the temperature change across a fault soon after a large earthquake. If you rub your hands together on a cold day, they get warmer because of the frictional heat. In the same way, a fault gets hotter from frictional heat when the two sides of a fault slide in opposite directions during an earthquake. From the observed temperature difference, the amount of generated heat, and thus the friction can be calculated. Working with colleagues at DPRI, one of my main research long-term objectives was to estimate the friction level by making fault-zone temperature measurements soon after large earthquakes.

There are several requirements needed for temperature measurements to estimate the friction. 1) The measurement needs to be done soon after the earthquake, preferably within about a year. 2) The fault slip where the temperature measurements are done has to large (several meters). 3) A borehole measurement is necessary because the fault is usually complicated at the surface and the displacement is usually not seismic slip (negligible stress drop). This means that the observed large fault slip needs to come to shallow depth that is accessible with a borehole (within 1 or 2 km).

2.1 1999 Chi-Chi, Taiwan Earthquake

The first chance to make fault-zone temperature measurements was following the 1999 Chi-Chi, Taiwan earthquake (Mw7.7) which produced large surface faulting over most of the 70 km length of the Chelungpu fault. The Taiwan Chelungpu-Fault Drilling Project (TCDP) was started to investigate the properties of the fault with boreholes into the fault-zone. The DPRI contribution was to make borehole temperature measurements across the fault zone to estimate the fault friction. Establishing the project and drilling the main borehole took time, so that the temperature measurements were done in 2005, which was 6 years after the earthquake. This was quite late and the temperature had mostly dissipated, but we still observed a small anomaly of about 0.06 °C across the fault in a region where the slip was 5 meters.

Fig. 4. Temperature instrument used in Taiwan

At this time there were no commercially available thermometers that could be used, so we contracted a company to build an instrument that had two quartz temperature sensors and data loggers. The instrument was about 6 meters long and quite heavy (Fig. 4). For this analysis, we used the residual temperature, which is the measured temperature minus the linear temperature gradient with depth. The residual temperature shows a small peak centered on the fault (solid line in Fig. 5). Fig. 5 also shows calculated values for the residual temperature assuming various values for the coefficient of friction (thin lines). The data are best fit with a coefficient of friction of 0.08. This is much lower than the laboratory values of 0.6 to 0.7 mentioned in section 2. This result was the first reported friction estimate from temperature measurements following an earthquake (Kano et al., 2006). However, the noise level in the data is relatively high and the measurement was done 6 years after the earthquake, so the reliability of the result might be questioned.

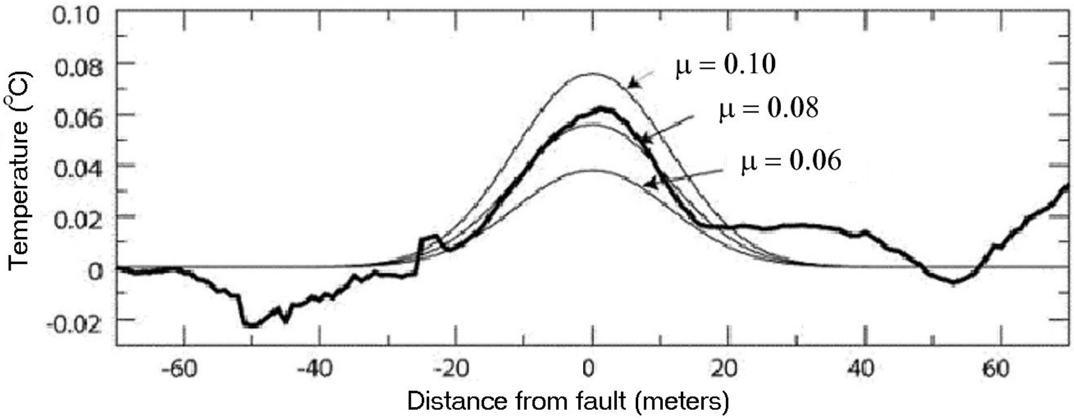


Fig. 5. Results of temperature measurement for Chi-Chi, Taiwan earthquake (thick black line) and model calculations for coefficients of friction values (thin lines) for 0.06, 0.08 and 0.10. From Kano et al., 2006.

2.2 2008 Wenchuan, China Earthquake

The second chance to make temperature measurements came following the 2008 Wenchuan, China earthquake (Mw7.9). This large earthquake produced surface faulting at many places along the Longmenshan Fault zone. The Wenchuan Fault Scientific Drilling project (WFSD) was established by the Institute of Geology, Chinese Academy of Geological Sciences, to drill a series of boreholes at several sites. We carried out temperature measurements in Hole 2 starting 10 months after the earthquake and continuing for 5 years. The borehole reached the fault at a depth of 595 meters. By this time there were commercially available temperature sensors that were much smaller and easier to use compared to the instrument we built for the Taiwan measurements.

The results from Li et al. (2015) in Fig. 6 show a small residual temperature anomaly of about 0.02 °C across the fault where the displacement was 7 meters. The temperature signal has a very small amplitude and the time dependence of the shape was not quite what we would expect for an anomaly caused by the frictional heat. Using the very small amplitude of the signal would give a coefficient of friction of much less than 0.1. Because of the unusual characteristic of the temperature anomaly, it is questionable if this is due to the fault friction. However, It can be concluded that the fault friction is not as large 0.6 to 0.7 because, in that case there would be a large anomaly that should be easily observed by our temperature measurements.

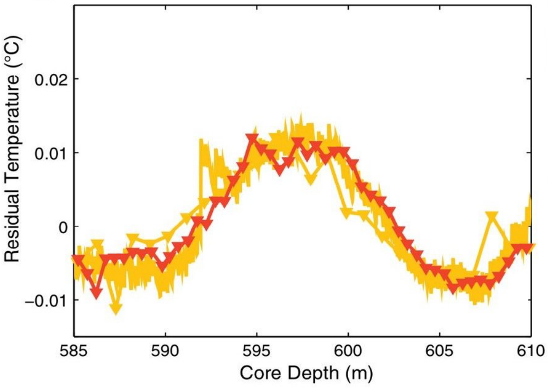


Fig. 6. Residual temperature for Wenchuan, China earthquake. From Li et al., 2015.

2.3 2011 Tohoku-oki Earthquake

The 2011 Tohoku-Chihou Taiheiyou-oki earthquake (Tohoku-oki earthquake) was the largest (Mw9.1) earthquake in Japan’s recorded history and a very important event in terms of seismological and tsunami research. Since the faulting near the Japan Trench came to shallow depth (less than 1 km), this was a prime location for another fault-zone drilling project to the friction level for a very large earthquake.

The Japan Trench Fast Drilling Project (JFAST) (Mori et al., 2014) was a large multi-country effort by the International Ocean Drilling Program (IODP) designed to study the shallow portion of the fault that had huge slip during the earthquake. It is important to understand this shallow slip because it is the main source of the large tsunami that devasted much of the Tohoku coastal region.

The research ship *Chikyu* was used to drill boreholes from the seafloor to the nearly horizontal fault. The depth of the fault from the seafloor was 815 meters. There were difficult technical problems because the water depth was nearly 7000 meters. After several borehole was drilled and a sample of fault retrieved, temperature sensors were place in one of the boreholes. The instruments continuously measured the temperature from August 2012 to April 2013.

Fig. 7 (from Fulton et al., 2013) shows the results of temperature measurements that were recorded during the time period from August to December 2012. Of the three fault zone temperature measurements described in this paper, the Tohoku-oki data are by far the best quality observations. The measurements were made relatively soon after the earthquake (17 to 21 months) and the slip of the fault was very large (50 m). The results of the residual temperatures show a clear anomaly across the fault with an amplitude of about 0.3 °C. The one-sided width of the anomaly is about 5 meters which matches the theoretically calculations. The inferred coefficient of friction from the modeling is 0.1.

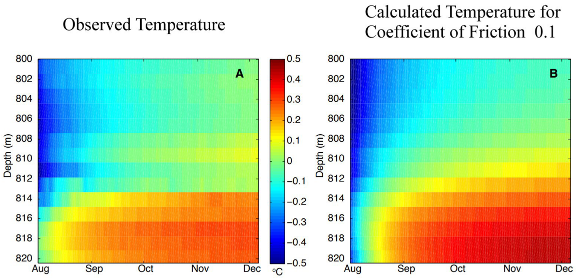
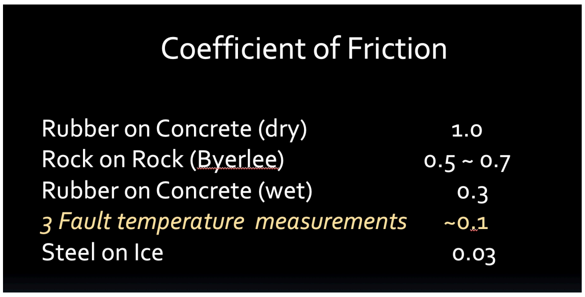


Fig. 7. Left: Observed residual temperature for the Tohoku-oki earthquake as a function of depth (vertical) and time (horizontal). Right: Calculated temperatures assuming a coefficient of friction of 0.1. From Fulton et al., 2013.

3. Summary and Conclusions

Table 1 summarizes the temperature measurements following large earthquakes for the three fault zones in Taiwan, China and Tohoku region. All three measurements show quite low coefficients of friction of about 0.1 or less. This result is quite different from the much higher values of rock friction that were obtained in laboratory experiments. It is rather surprising that the fault rocks can slip with such low friction. For example, Fig. 8 lists some values of coefficient of friction for various materials. Our results show that the friction level is between rubber on wet concrete (car tire on a rainy day) and steel on ice (ice skating).

One important difference between the rock mechanics experiments and our temperature results, is that the laboratory results are for small displacements and reflect values similar to the static friction. In contrast, the temperature measurements reflect the heat during the time of the large slip of the earthquake, so they represent the dynamic friction. The static friction of the fault is likely quite high and close to the laboratory values of friction, however, once the slip begins on the fault, the friction drops to a lower value of dynamic friction. The drop of friction during slip of a large earthquake (slip-weakening) has been previously proposed and may be due to thermal pressurization (Rice, 2006) or other mechanisms, such as mechanical lubrication or flash heating. This difference between static and dynamic friction can explain the San Andreas Fault Heat Paradox. The static friction of the fault zone rocks is relatively high when the fault is not slipping but slip-weakening mechanisms cause the drop of dynamic friction to lower values when the large slip occurs. The heat flow values reflect the dynamic friction levels.



Coefficient of Friction

Rubber on Concrete (dry)	1.0
Rock on Rock (Byerlee)	0.5 ~ 0.7
Rubber on Concrete (wet)	0.3
3 Fault temperature measurements	~0.1
Steel on Ice	0.03

Fig. 8. Coefficient of friction for various materials.

Earthquake	Mw	Date	Fault	Time After Eq. (months)	Depth (m)	Slip (m)	Temp (ºC)	Coeff. of Friction
Chi-Chi Taiwan	7.7	21/09/1999	Chelungpu	72	1111	5	0.06	0.08
Wenchuan China	7.9	12/05/2008	Longmenshan	10-60	595	7	0.02	< 0.1
Tohoku-oki Japan	9.1	11/03/2011	Japan Trench	21	815	50	0.3	0.1

Table 1. Summary of fault-zone temperature measurements.

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