mechanism of LRF action may lead to new opportunities to inhibit Notch for therapeutic purposes. Because LRF is broadly expressed, it will also be interesting to determine whether this factor influences Notch signaling at other stages of hematolymphoid development, and in tissues such as the vasculature, gut, brain, and skin, where Notch function is critical. This versatility of Notch, and the ubiquity of its signaling pathway components, require its tight regulation to achieve specificity. LRF appears to keep Notch on just such a tight leash.

References

GEOPHYSICS

Slippery When Hot

Raul Madariaga

Most earthquakes in Earth’s crust are caused by fast slip on preexisting faults. Slip on faults explains well the emission of seismic waves, but it does not address how friction between rocks is overcome, especially at the fast rates at which earthquakes slip. On page 878 of this issue, Han et al. (1) address this question in a laboratory experiment.

The authors studied friction at high speeds between two precut cylindrical bars of Carrara marble cut along a section perpendicular to the axis of the cylinder. They found that friction decreases as a result of rapid, localized heating produced by high slip rates. Calcite, the main constituent of marble, decomposes into small particles of lime (CaO), forming a narrow zone of powder (called fault gauge) and producing a substantial amount of CO2. The reduction in friction is so dramatic that when the slip rate increases beyond about 50 cm/s, the fault effectively slips freely. Marble is not the typical rock lining seismic faults, but nevertheless the authors attribute the reduction in friction to low-strength minerals like talc. The work provides new insight into friction at high speeds that may help to solve some long-standing puzzles in earthquake science, but it also raises questions regarding the scaling of stresses in seismic ruptures.

Early kinematic models of seismic slip on faults did not take into account the frictional properties of the fault, because seismic radiation could be computed independently of the actual stresses that operated on the fault. These models were highly successful and led to a broad understanding of earthquake kinematics. In the early 1970s, seismologists realized that friction had a fundamental role in determining the dynamics of earthquakes. Yet the actual properties of friction remained elusive, because experiments on rock friction could only be done at speeds of less than 1 mm/s, whereas earthquake slip occurs at rates closer to 1 m/s.

The most basic information about rock friction was found by Byerlee (2), who showed that static friction (the resistance to the initiation of slip on the fault) varied between 0.6 and 0.8 times the confining pressure (the pressure that holds the rocks together in the deep Earth) for almost all.

Laboratory experiments provide a possible explanation for why friction between rocks does not impede the slippage that leads to earthquakes.

Slip distribution during an earthquake. The image shows the slip distribution 15 s into the Landers earthquake of 28 June 1992 in the Mojave Desert, southern California (8, 9). In the figure, the set of faults that slipped during the earthquake are viewed from the west, with the slip distribution pasted on. Rupture started from the southern end (right in this figure) and propagated along several fault strands at an average speed of 2.5 km/s. At the time of the image, rupture is starting to propagate into the last segment.

The image shows the slip distribution 15 s into the Landers earthquake of 28 June 1992 in the Mojave Desert, southern California (8, 9). In the figure, the set of faults that slipped during the earthquake are viewed from the west, with the slip distribution pasted on top of them. Rupture started from the southern end (right in this figure) and propagated along several fault strands at an average speed of 2.5 km/s. At the time of the image, rupture is starting to propagate into the last segment.

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Landers earthquake (28 June 1992)

Slip distribution during an earthquake. The image shows the slip distribution 15 s into the Landers earthquake of 28 June 1992 in the Mojave Desert, southern California (8, 9). In the figure, the set of faults that slipped during the earthquake are viewed from the west, with the slip distribution pasted on top of them. Rupture started from the southern end (right in this figure) and propagated along several fault strands at an average speed of 2.5 km/s. At the time of the image, rupture is starting to propagate into the last segment.
rock samples. These results led to the slip-weakening model, in which friction was assumed to decrease as slip on the fault increased. The key model parameter was the slip-weakening distance (the amount of slip required to reduce friction at high speeds). This phenomenological model avoided the difficult question of the origin of friction.

Mechanical studies of rocks in the late 1970s provided the first experimental evidence that steady-state friction indeed decreased logarithmically with slip rate. Friction also depends on several parameters representing the state of the slipping surface. In these experiments, designed to understand friction at low slip rates, the slip-weakening distance is very small, on the order of a fraction of 1 mm.

In the past 15 years, seismologists were able to study in detail several major earthquakes in the United States, Japan, Turkey, and Taiwan. The slip-weakening distances inferred for these events were several orders of magnitude longer than those observed in rate-and-state friction experiments. A simple scaling argument explains the long slip distances. Earthquakes are similar for a broad range of scales, at least from magnitudes of about 4 to 8; the single scaling variable appears to be the length of the fault. If this is the case, then slip-weakening distances must scale with earthquake size; otherwise, either large earthquakes would all propagate with rupture speeds higher than that of shear waves, or small events could never occur because of the high frictional resistance of the faults. Han et al. find that slip weakening occurs on scales on the order of a meter, a value that is very close to the slip-weakening distances observed in earthquakes of magnitude around 7. A numerical simulation of the Landers earthquake of 28 June 1992 in California (see the figure) required slip weakening distances of several tens of centimeters, similar to those observed by Han et al.

The experiments by Han et al. show that friction is very sensitive to slip rate. Large slip-rate weakening favors the creation of rupture pulses instead of long cracks. In pulses (4), slip occurs in a narrow zone that follows the rupture front; this is a very efficient way to propagate seismic slip while maintaining a high average stress on the fault. The results reported by Han et al. may also help to explain the "San Andreas Fault paradox": There is no observed increase in heat flow near the fault, which means either that the fault is very weak during slip, producing very little heat, or that friction is high but heat is evacuated by fluid flow (5). The experiments also raise several questions. The most obvious is that they were done at a fixed slip rate, whereas earthquakes are intrinsically transient phenomena, with slip rate increasing from zero to speeds on the order of 1 m/s when the rupture front arrives, finally decreasing to zero as the fault heals. It remains unclear whether the friction law derived in this work applies to transient slip of short duration.

By far the most important question concerns scaling. Han et al. carried out their experiments at confining pressures of 7.3 MPa. Will the same friction law apply at much higher confining pressures that prevail in seismogenic zones? Seismic data have shown that slip rates are proportional to stress drop (the difference between the static and dynamic friction). Stress drops in the experiments were on the order of 7 MPa at the confining pressure of 13 MPa. Extrapolating to the depths where earthquakes occur, this implies stress drops at least an order of magnitude greater than those observed. Furthermore, the experiments were done on marble; the results may be different for the silicate rocks found at 10 km depth.

Thermal weakening is not the only mechanism that may reduce friction at high slip rates; melting (6) is another example. Furthermore, direct application of the results reported by Han et al. actual fault zones depends on the assumption that slip is concentrated on a narrow band. Recent experiments on sand have shown (7) that slip bands tend to form outside the main slip zones as fault zones evolve toward large accumulated slip. We are only at the beginning stages of a fresh understanding of fast frictional processes in earthquakes.

References

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Titan’s Organic Factory

Sushil Atreya

Researchers have identified molecules in the atmosphere of one of Saturn’s moons that are responsible for its smog-like haze.

Since its discovery by Christiaan Huygens in 1655, Saturn’s large moon Titan has intrigued scientists, not the least because its surface is blanketed by a thick haze. This haze plays an important role in warming Titan’s nitrogen atmosphere, preventing its condensation and subsequent removal. However, the most important aspect of Titan’s haze may be its composition. It has long been suspected that the haze results from complex organic molecules, perhaps even prebiotic molecules (1). Now, close flybys of Titan by the Cassini spacecraft reveal that such molecules may indeed be forming. On page 870 of this issue, Waite et al. (2) report identification of benzene, along with both positively and negatively charged organic ions. Heavy molecules formed from these ions eventually produce Titan’s upper haze layers and are expected to contribute substantially to the total haze content of the atmosphere.

Unlike the other moons in the solar system, Titan has a massive atmosphere, consisting of 95% nitrogen and 5% methane. Chemical processes are initiated by the break-up of these gas molecules by solar radiation and charged particle collisions (see the figure). Even though Titan receives only 1% of the solar ultraviolet flux that Earth does, and is bombarded by charged particles from Saturn’s magnetosphere only some of the time, this energy is sufficient for photochemistry to proceed efficiently. Simple hydrocarbons—such as ethane, acetylene, and diacetylene—and nitriles, such as hydrogen cyanide (HCN) and cyanogen (C$_2$N$_2$) form readily. Somewhat
beamng resulted from a blunt (18) or asymmetric shock (2). The asymmetric shock could result from an interstellar magnetic field inclined in a particular direction (19, 20). In a recent report (3), we showed that an interstellar magnetic field in the HDP could distort the termination shock in a direction that explains the TSPs streaming outward at V1.

Figure 2 shows that for \( B_{\text{ISM}} \) parallel to the HDP, the longitude of the MD point (the minimum radial distance of the termination shock to the Sun) is greater than the longitude of V1, so the TSPs will stream outward along the spiral field. In the heliospheric southern hemisphere the longitude of V2 is greater than that of the MD point of the shock, so the TSPs will stream inward toward V2, as is observed. However, for \( B_{\text{ISM}} \) parallel to the GAL, the MD in the northern hemisphere shifts to a smaller longitude than V1, so that the TSPs would stream inward toward V1, opposite to what is observed.

In this calculation we did not include the neutral hydrogen atoms that interact with the ionized component by charge exchange. Although the inclusion of the neutral atoms will tend to symmetrize the solution and quantitatively affect the inclusion of the neutral atoms will tend to symmetrize the solution and quantitatively affect the degree of asymmetry, the general character of the asymmetry is expected to remain the same, with the plane of symmetry of the distorted heliospheric field determined by the plane of the local interstellar magnetic field (21, 22). Thus, it would be expected that different orientations of the local interstellar magnetic field would result in the same qualitative differences in the predicted radio source locations and streaming directions of upstream ions as described here. On the basis of those differences, and assuming that the source of radio emission is the region where the field draped on the heliopause is perpendicular to the radial direction, we find from Voyager observations that the plane of the local interstellar magnetic field is not parallel to the GAL but is 60° to 90° from that plane (rotated clockwise from a view from the Sun). This suggests that the field orientation in the Local Interstellar Cloud differs from that of a larger-scale interstellar magnetic field thought to parallel the GAL.

References and Notes

Ultralow Friction of Carbonate Faults Caused by Thermal Decomposition

Raehee Han,1,* Toshihiko Shimamoto,2† Takehiro Hirose,2† Jin-Han Ree,3 Jun-ichi Ando3

High-velocity weakening of faults may drive fault motion during large earthquakes. Experiments on simulated faults in Carrara marble at slip rates up to 1.3 meters per second demonstrate that thermal decomposition of calcite due to frictional heating induces pronounced fault weakening with steady-state friction coefficients as low as 0.06. Decomposition produces particles of tens of nanometers in size, and the ultralow friction appears to be associated with the flash heating on an ultrafine decomposition product. Thus, thermal decomposition may be an important process for the dynamic weakening of faults.

The strength of seismogenic faults, which is frictional resistance to fault slip during earthquakes, has been a major subject of debate in fault mechanics for 30 years (1, 2). Although the stress–heat flow paradox for the San Andreas fault (no heat-flow anomaly, contrary to the prediction from in situ stress measurement and laboratory data of rock friction) favors extremely low fault strength (3, 4), reasons for the weakness have been unclear. Recent work has shown that the dynamic weakening of faults during seismic slip can be caused by mechanisms such as frictional melting (5–9), thermal pressurization (10–13), and silica-gel formation (14, 15). Fault gouge was also shown to exhibit pronounced slip weakening at high slip rates (16), presumably because of flash heating (13). Some analyses have predicted that slip-weakening distance, over which the initial peak friction drops to steady-state dynamic friction (8, 12), and fracture energy (13, 16) are of the same order as those parameters that are determined seismologically, narrowing the gap between laboratory studies of fault mechanics and seismology. Modeling the generation of large earthquakes is now becoming possible on the basis of the measured mechanical and transport properties of fault zones. Moreover, the dynamic weakening of faults may explain the lack of heat-flow anomaly after earthquake events along the San Andreas fault.

Thermal decomposition of rock-forming minerals at high ambient temperature and pressure can dramatically lower the strength of rocks because of the buildup of pore fluid pressure and the associated reduction of effective normal stress, provided that the sample is effectively undrained (17). Even at shallow crustal levels with low ambient temperature, thermal decomposition may occur at an elevated temperature because of coseismic frictional heating along fault zones. We demonstrated that a carbonate fault can lose frictional strength almost completely because of the thermal decomposition of calcite caused by frictional heating during high-velocity friction experiments on Carrara marble at seismic slip rates.

Forty-two friction experiments were conducted on precut bare surfaces of a pair of solid cylindrical specimens of Carrara marble (~99% calcite) at room temperature and room humidity. The experiments were carried out at normal stresses of 1.1 to 13.4 MPa and at equivalent slip rates of 0.03 to 1.30 m s\(^{-1}\), with a rotary-shear, high-velocity friction apparatus at Kyoto University (18). The diameter and length of the specimen were 21.8 to 24.8 mm and about 20 mm, respectively (19). Because there is a slip-rate gradient across the fault due to cylindrical specimen geometry, we use the term “equivalent slip rate” (“slip rate” or “velocity” hereafter) (7, 18, 19).
At different slip rates (Fig. 1A), the friction coefficient of the specimens decreased nearly exponentially from peak friction, $\mu_p$, to nearly steady-state friction, $\mu_{ss}$ (20), with increasing displacement. The slip-weakening distance ranged from a few to several meters. The $\mu_p$ decreased markedly from ~0.6 to a range of 0.04 to 0.11 with an increase in slip rate (Fig. 1B). A linear friction law holds for both peak and steady-state friction, yielding $\mu_p$ of 0.60 ± 0.01 and $\mu_{ss}$ of 0.06 ± 0.01 (Fig. 1C). This $\mu_p$ value is more or less typical for marble (0.4 to 0.8) from conventional slow slip-rate (<1 mm s$^{-1}$) experiments (21). But $\mu_{ss}$ at a high slip rate (1.1 to 1.2 m s$^{-1}$) was extremely low. In contrast, $\mu_{ss}$ values remained high (0.46 to 0.63) at slow slip rates (0.03 to 0.08 m s$^{-1}$).

Microstructural observations and electron probe microanalysis of deformed specimens were conducted on thin sections normal to the fault and parallel to the slip direction. We started experiments with precut surfaces of Carrara marble, but gouge zones formed very quickly on both sides of the slip surface, which nearly coincides with the precut surface (Fig. 2A). Samples were collected from the slip surface for observations with a field-emission scanning electron microscope (FE-SEM) and a transmission electron microscope (TEM) and for x-ray diffraction (XRD) analyses. Those analyses revealed that the gouge zone forms at a very early stage of displacement (<2 m), when the outer and inner zones of gouge consist of calcite and lime (CaO) and/or hydrated lime [Ca(OH)$_2$], respectively. In the host rock adjacent to the fault gouge, fracturing of calcite grains occurred, and the size of calcite fragments decreased toward the slip surface to become calcite gouge. Calcite thermally decomposes into lime and CO$_2$ gas at about 720 to 900°C (22, 23), and the lime can be transformed to hydrated lime by absorbing moisture when it is exposed to the atmosphere. Thus, thermal decomposition of calcite occurred from a very early stage of slip.

Many fractures were present over a wide decomposition zone between the decomposition fronts (DFs) (Fig. 2A); those fractures must have increased permeability. The decomposed zone consisted of granulike aggregates ranging from about 100 to a few hundred nanometers in diameter (Fig. 2B), but each aggregate was composed of ultrafine grains that were several to a few tens of nanometers in size (Fig. 2C and fig. S3). Calcite decomposition was confirmed in specimens at fast slip rates (>0.4 m s$^{-1}$), but no evidence of decomposition was present in a specimen deformed at a slow slip rate of 0.08 m s$^{-1}$ (run number HVR522; compare XRD curves in Fig. 2D).

We did not recognize glass or amorphous material in any of the specimens (fig. S3).

To determine the timing of decomposition with respect to the slip-weakening behavior, we measured the emission of CO$_2$ released from a deforming sample by using two solid electrolyte-type CO$_2$ sensors (19). Sensor 1 (without a filter) was set very close to the fault (about 30 mm away) but the CO$_2$ sensor showed the highest counts per second (cps) on all vertical axes.

**Fig. 1.** Frictional properties of simulated faults in Carrara marble at subseismic to seismic slip rates. (A) Friction coefficient versus fault displacement for five runs conducted at different slip rates and at a normal stress of 7.3 MPa (except for HVR522 at 4.9 MPa). The dashed black rectangle shows an example of the range of data used for the estimation of steady-state friction. (B) $\mu_p$ plotted against the slip rate for 10 runs conducted at a normal stress of 7.3 MPa. Vertical bars show the SD of $\mu_p$ (shown only when the SD is greater than the box size). (C) Shear stresses plotted against normal stresses at peak and steady-state friction at slip rates of 1.14 to 1.18 m s$^{-1}$. Open squares and circles indicate initial peak friction and steady-state friction, respectively. The slopes of the lines give frictional coefficients at peak and steady-state friction. $\tau$, shear stress; $\sigma_n$, normal stress.

**Fig. 2.** Textures and decomposition products in fault zones. (A) A cross-polarized light photomicrograph of a thermally induced decomposition zone developed in Carrara marble, deformed at a slip rate of 1.30 m s$^{-1}$ and at a normal stress of 4.6 MPa (HVR398, total slip = 125 m). DFs are between the wall rock and the decomposition zone. Slip was highly localized along the surface denoted by “slip surface.” (B and C) SEM and TEM photomicrographs, respectively, illustrating microstructures of the lime (CaO) aggregates on the slip interface. (D) XRD spectra of an undeformed specimen, a preheated specimen, and specimens deformed at different conditions. Diffraction intensity is shown in 1000 × counts per second (cps) on all vertical axes.
The decomposed specimens could no longer emit CO2 gas. The behavior is markedly similar between faults in Carrara marble and in decomposed specimens (Fig. 4). We have not measured the permeability of the decomposed zone in marble yet. But fractures in the decomposed zone in Fig. 2A suggest that the permeability of the decomposed zone is large enough for CO2 to escape and to prevent the buildup of high pore fluid pressures. Enhanced permeability during the dehydration of serpentinite at elevated ambient temperatures (not due to frictional heating) was also confirmed recently (25).

These results indicate that the weakening is attributed not to CO2 pressure but to the low frictional strength of newly formed ultraline lime grains. Among other possibilities, frictional melting can be immediately removed because calcite decomposition occurs before melting. Also, CaO melting would be unlikely because its melting temperature (~2572°C) is much higher than the temperatures recorded at the slip interface. Indeed, we did not detect any glass or amorphous materials in fault zones (fig. S3). Wrinkle-like pulses or normal separation of a fault along a bimaterial interface (26) is also unlikely because there is no material contrast across a fault in our experiments.

In view of the existing data, we considered that flash heating (13) at interfaces of ultraline particles is critical for pronounced weakening of carbonate fault. The weakening by flash heating or transient local heating at asperity contacts has been proposed to occur via local melting at asperity contacts and/or by strength degradation of asperity contacts at submelting temperatures (13). The latter case is more likely for decomposed calcite because lime has a very high melting temperature. However, exact deformation mechanisms along sliding asperity or grain contacts still remain to be explored.

To demonstrate the importance of temperature rise during high-velocity sliding, we measured the temperature along the fault of the specimens (Fig. 3, C and D), using a radiation thermometer (19, 27) during a run conducted at about the same sliding condition as that in HVR601. The thermometer measured an average temperature higher than 550°C over an area of 0.4 mm in diameter with a fast response time (~0.1 s). The measured temperature reached a maximum of 950°C at 30 s (high enough for calcite decomposition) after attaining about 650°C during the first 9 s (Fig. 3C). The local temperature at sliding asperities should be higher than the measured surface temperature even in the early stage (<9 s), in view of the CO2 emission data (Fig. 3, A and B). The friction and thermal evolution in the final stages of the experiment are very interesting. After the specimen was disconnected from the motor, fault slip decelerated and stopped in about 3 s (Fig. 3, C and D). Friction increased at an accelerating rate as the temperature fell. The inverse relation between friction and temperature strongly suggests that the immediate strength recovery could be related to a rapid drop in temperature.

The simulated faults of Carrara marble exhibit lower friction than does the Nojima fault gouge, although their overall behaviors are similar (16). A possible reason for this difference is a very effective production of ultraline grains that are tens of nanometers in diameter (Fig. 2C) by a
decomposition reaction (no time for grain growth during seismic-fault motion). The process may be similar to the cases of intermediate- to deep-focus earthquakes, for which the formation of ultrafine reaction products may play a decisive role in earthquake generation (28). Other gouge materials have to undergo grain comminution to form ultrafine grains, which requires extra work in fault zones, resulting in higher friction. For slip on faults in Carrara marble, understanding friction between nanometer-scale particles seems to be a key for delineating the exact mechanisms of the dynamic weakening of faults.

Our results have important implications for earthquake geology and fault mechanics. Marked decomposition weakening may be a widespread phenomenon, because fault gouges commonly contain sheet silicate minerals that decompose even at lower temperatures than that for calcite decomposition, although thermal decomposition of sheet silicates may be followed by frictional melting (29). Also, thermally induced decomposition may leave geological evidence (other than pseudotachlytes) of seismic-fault slip, contrary to geologists’ opinion that faults do not preserve a record of seismic slip, except for the small percentage of faults containing pseudotachlyte (30). Indeed, we have shown that coseismic decomposition of siderite produces a stable mineral, magnetite (31). Thus, the clear demonstration of thermal decomposition during seismic slip opens up a new series of investigations in integrated fault and earthquake studies.

References and Notes

19. Materials and methods are available as supporting material on Science Online.
20. \( \mu_0 \) is the ratio of the highest shear stress to normal stress before the onset of weakening, and \( \mu_s \) is the ratio of steady-state shear stress to normal stress.
24. The calculated bulk temperature (~850°C) on the sliding surface after 0.2 s appears to be consistent with the immediate decomposition after the onset of slip (19).
32. The observations of the experimental specimens were made with the use of TEM (JEOL-JEM-2010) at the Natural Science Center for Basic Research and Development of Hiroshima University and FE-SEM (JEOL JSM-T7000F) at Geodynamics Research Center of Ehime University. This work was supported by the Brain Korea 21 Project of the Ministry of Education, Korea Research Foundation grant C00435 (100699), the Grant-in-Aid for Scientific Research, Japan Society for Promotion of Science (16340129 and 18340159), and the Center of Excellence Program for the 21st Century of Kyoto University, “Active Geosphere Investigation.”

Supporting Online Material

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Materials and Methods
Figs. S1 to S4

References
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GRACE Gravity Data Constrain Ancient Ice Geometries and Continental Dynamics over Laurentia

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The free-air gravity trend over Canada, derived from the Gravity Recovery and Climate Experiment (GRACE) satellite mission, robustly isolates the gravity signal associated with glacial isostatic adjustment (GIA) from the longer-time scale mantle convection process. This trend proves that the ancient Laurentian ice complex was composed of two large domes to the west and east of Hudson Bay, in accord with one of two classes of earlier reconstructions. Moreover, GIA models that reconcile the peak rates contribute ~25 to ~45% to the observed static gravity field, which represents an important boundary condition on the buoyancy of the continental tectosphere.

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He similarity between the geometry of the free-air gravity anomaly (FAGA) over Laurentia (I) and the perimeter of the ancient ice complex that covered the region led to a long-held view that the perturbation largely

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have, on the basis of GIA modeling combined with an analysis of the spatio-spectral content of the Laurentian gravity field, proposed an intermediate scenario in which GIA and convection contribute roughly equally to the observed signal.

The characteristic time scale of GIA (a few thousand years) is orders of magnitude shorter than that of convective flow. Accordingly, Mitrovica and Peltier (4) suggested that consideration of the time rate of change of the gravity field would, when it became available, provide a robust method for isolating the GIA signal. The trend field would also provide finer spatial resolution of ice-sheet history than the static field. Observational constraints on gravity trends from land-based surveys in Hudson Bay exist (11, 12), but these are too sparse to accurately constrain the regional (and peak) GIA signal. Recently, measurements obtained by the GRACE satellite mission (13) have reached sufficient time span to yield useful constraints on regional gravity trends. Our goal is to make use of the GRACE data to constrain the GIA signal and thus test the suite of published models for the dynamics of the Laurentian craton. We also use the GRACE-derived maps of gravity rates to address a century-long debate concerning the geometry of late Pleistocene ice cover over the region.

We use monthly Center for Space Research (CSR) RL01 GRACE solutions for the geoid,
CORRECTIONS & CLARIFICATIONS

ERRATUM
Post date 17 August 2007

Reports: “Ultralow friction of carbonate faults caused by thermal decomposition” by R. Han et al. (11 May 2007, p. 878). Color traces appeared incorrectly in Fig. 2D; Fig. 3, A, C, and D; and Fig. 4. The corrected figures are shown here.

![Corrected figures](image-url)
Supporting Online Material for

Ultralow Friction of Carbonate Faults Caused by Thermal Decomposition

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Materials and Methods
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Ultra-low friction of carbonate faults caused by thermal decomposition
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Materials and Methods

Specimen configuration and equivalent slip-rate
Each experiment was conducted on a pair of solid cylindrical specimens of Carrara marble (pure calcite rock from Italy) (Fig. S1). The diameter and length of the specimen are 21.8 to 24.8 mm and about 20 mm, respectively. We used solid- rather than hollow-cylindrical specimens because the latter cannot support high normal stress. To prevent thermal fracturing of the specimens due to rapid and inhomogeneous frictional heating on sliding, we mounted an aluminium sleeve (~1.3 mm thick) around each specimen with a diameter of 21.8 mm and a narrow gap was left between the two aluminium sleeves to avoid metal-to-metal frictional contact, except one pair of the larger specimens (24.8 mm in diameter) for which no aluminium sleeve was used. All of our friction tests were conducted on bare surface of solid rock cylinder without pre-inserting any gouge between the specimens.

Since there is a slip-rate gradient across the fault plane due to the configuration of the cylindrical specimens (increasing slip rate from the center to the periphery of the specimen), we use ‘equivalent slip rate’ ($S_1$, $S_2$) here. Assuming no velocity dependence of the shear stress, the total frictional work on a fault per unit time, $W$, is defined by

$$W = \tau V A = \frac{4}{3} \pi^2 R \tau (r_2^2 - r_1^2)$$

where $\tau$ is shear stress, $V$ is equivalent slip rate, $A$ is fault area, $R$ is rotation rate, $r_1$ and $r_2$ are the inner and the outer radii of a hollow cylindrical specimen, respectively. Since the fault area, $A$, is $\pi (r_2^2 - r_1^2)$, the equivalent slip rate is given by
\[ V = \frac{4\pi R(r_1^2 + r_1 r_2 + r_2^2)}{3(r_1 + r_2)} . \]

For our solid cylindrical specimens, where \( r_1 = 0 \), the above equation is written as below:

\[ V = \frac{4\pi Rr}{3} \]

where \( r \) is the radius of the solid cylindrical specimen.

**CO₂ concentration measurement**

We measured the emission of CO₂ released from deforming specimens using two solid electrolyte-type CO₂ sensors (TGS4161 with an accuracy of about 20 %; Figaro Co. Ltd., Osaka, Japan). Commercially available sensors of this type have a filter protecting the sensor. As this filter retards the response of the sensor, we used two sensors, one with and one without a filter. Sensor 1 (without a filter) was set very close to fault (about 30 mm away) to detect the onset of decomposition. It takes for this sensor about 0.9-1.0 s to yield an initial DC output and about 10 s to give outputs corresponding to the 90 % of CO₂ concentration when the sensor is instantly exposed to an atmosphere with a different CO₂ concentration. Sensor 2 with a filter has the initial response time of about 2 s and 90 % response time of around 90 s. This sensor was used to determine the total amount of CO₂ emission by putting it on a corner of the specimen chamber, sealed with tapes as much as possible, and by monitoring CO₂ concentration until the output becomes stable after the completion of experiment. The location of the sensors is shown in Fig. S2. The sensor output was directly recorded in mV for sensor 1 to shorten its response time, whereas the sensor output was transformed with an IC circuit to convert the output to CO₂ concentration in ppm for sensor 2. Neither of these sensors can yield real-time changes in CO₂ concentration accurately since it takes the sensors tens of seconds or longer to give output corresponding to the concentration.

**Temperature measurement**

We used a radiation thermometer (Minolta, TR-630A) to measure temperature along the sliding surface. The thermometer detects radiation energy emitted from a body.
and the radiation enters through optical lenses into the thermometer and then is transformed into current. The thermometer equipped with a close-up lens can detect radiation energy from a small area (0.4 mm in diameter) at the measuring distance of about 20 cm that represents an average bulk temperature over the small area, but cannot give us any information on the local temperature over smaller areas. The ‘minimum’ detectable temperature is about 550 °C.

Experiment on pre-heated specimens and treatment of specimens

We statically heated three cylindrical specimens of Carrara marble in the oven and all the specimens were taken out of the oven at the same time and cooled in room-air. Then, we measured the weight of the specimens to check if the heating time (one and a half hours at 900 to 904 °C) was enough for the complete decomposition of the specimens and found that the weight after heating was the same as the expected weight of a fully decomposed specimen. Two of them were jacketed with aluminium sleeves and the other specimen was kept in a plastic zipper bag for the later XRD analysis. Two jacketed specimens were loaded into the friction testing apparatus and we conducted the run, HVR739. All these procedures under room-humidity condition before starting the run took less than 20 minutes. XRD analysis on the pre-heated specimen was conducted several hours later, and the X-ray diffraction spectrum for the pre-heated specimen shows strong peaks of lime and very weak, almost unnoticeable, peaks of hydrated lime without calcite peak (Fig. 2D). No peak of calcite excludes the possibility of the re-carbonation of lime which requires sequential reactions including hydration of lime followed by slow re-carbonation reaction of hydrated lime into calcite by absorbing CO₂ from air (S3). The very weak peaks of hydrated lime in the pre-decomposed specimen (Fig. 2D) raises the possibility that at least a very small amount of lime may have been hydrated when the specimen had been exposed to room humidity less than 20 minutes before the run. The hydration of lime during static heating (and friction tests at high slip rates) is unlikely, since the decomposition temperature of hydrated lime (470-640 °C, S4) is lower than that of calcite.

Concerning the question whether the possible presence of very small, if any, amount of hydrated lime has a significant effect on the strength of the fault zones consisting of lime grains, we note the weakening in the slide-hold-slide tests under room-humidity condition. In the second slide after a hold (no slide) time of up to several tens of minutes (during which the hydration of lime formed in the first slide may have occurred), the weakening was almost the same as that in the friction tests conducted at the same normal
stress and slip rate but with Ar flowing (or dry) condition. Thus, these experimental results indicate that the mechanical effect of the possible dehydration of hydrated lime is not significant.

For our early specimens carelessly left under room humidity after runs, we certainly confirmed the presence of hydrated lime (e.g. HVR464 in Fig. 2D). However, no hydrated lime was detected in specimens which were carefully stored in a desiccator with silica gel after runs (e.g. HVR520 in Fig. 2D). Thus, hydrated lime is unlikely to have formed along faults during friction experiments.

Material on slip localization surface: SEM and TEM observation

After the experiments, we observed shiny slip surfaces (or slickensides) along which slip was localized. We conducted X-ray diffraction (XRD) analysis on the material collected from the slip localization surface. New diffraction peaks of lime (and/or hydrated lime) and the significant reduction of the diffraction intensity of calcite were detected compared to undeformed specimen, indicating thermal decomposition of calcite into lime (Fig. 2D). In the analysis, no evidence of amorphous material was identified. For more detailed observation on the material collected from the slip localization surface, we have conducted field-emission scanning electron microscopy (FE-SEM) and transmission electron microscopy (TEM) (Fig. S3). The TEM sample was collected from the slip surface and was dispersed in ethanol, and then a drop of ethanol was placed on a Cu grid and was covered with a formvar film. Grain aggregates of about 100 to few hundred nanometers occur and each aggregate consists of ultrafine lime grains of several to a few tens of nanometers in diameter (Fig. 2B, 2C). Those grains are so fine that it is not clear if fault slip took place along a planar surface or within a slip zone of finite width. The use of the term, “slip surface”, does not imply that slip takes place along purely planar surface since calcite gouge zone is deformed.

A selected area electron diffraction (SAED) pattern taken from the material on the slip surface shows that the material is not glass but crystalline lime (Fig. S3). The lime grains formed by thermal decomposition of calcite are unlikely to be molten since its melting temperature is too high (~2,572 °C). Furthermore, temperature on the slip surface usually decreases consistently with decreasing friction during the weakening. Thus, the weakening is more likely associated with thermal decomposition of calcite rather than melting.
Calculation of bulk temperature rise in the very early stage of HVR601

The bulk temperature rise on the sliding surface \((S5)\) is:

\[
\Delta T = 2\tau V \sqrt{t} / (c_p \rho \sqrt{\pi \kappa})
\]

where \(\tau\) is shear stress, \(V\) is slip rate, \(t\) is time, \(c_p\) is specific heat, \(\rho\) is density and \(\kappa\) is thermal diffusivity. For the rock properties chosen for calcite marble and the sliding condition in HVR601 (\(\tau = 4.7\) MPa, \(V = 0.72\) m s\(^{-1}\), \(c_p = 835\) J kg\(^{-1}\) K\(^{-1}\), \(\rho = 2,710\) kg m\(^{-3}\), \(\kappa = 0.81\) \(10^{-6}\) m\(^2\) s\(^{-1}\)), the estimated bulk temperature is as high as 850 °C in 0.2 s (before the onset of weakening). Furthermore, the flash temperature at the asperity contacts should be much higher than the bulk temperature \((S6)\), which may indicate that thermal decomposition occurred almost immediately after the onset of slip in HVR601 (Fig. 3A, 3B) and is consistent with the observed CO2 emission.

**Fig. S1.** Specimen configuration used in this study. Each experiment was conducted on a pair of solid cylindrical specimen of Carrara marble (pure calcite rock from Italy). We used solid- rather than hollow-cylindrical specimens because the latter cannot support high normal stress. To prevent thermal fracturing of the specimens due to rapid and inhomogeneous frictional heating on sliding, we mounted an aluminium sleeve (\(~1.3\) mm thick) around each specimen with a diameter of 21.8 mm and a narrow gap was left between the two aluminium sleeves to avoid metal-to-metal frictional contact, except one pair of the larger specimens (24.8 mm in diameter) for which no aluminium sleeve was used. All of our friction tests were conducted on bare surface of solid rock cylinder without pre-inserting any gouge between the specimens.
**Fig. S2.** CO₂ sensors set for monitoring of CO₂ emission during experiment. Sensor 1 without a filter was set very close to fault (about 30 mm away) to detect the onset of decomposition. Sensor 2 with a filter was used to determine the total amount of CO₂ emission by putting it on a corner of the specimen chamber.
**Fig. S3.** SEM photomicrographs (A, B), TEM photomicrograph (C) and selected area electron diffraction (SAED) image (D) taken from the material on the slip surface (or slip localization surface). Slickenside surface with tracks is shown in the dashed red box in A. The material taken from the sliding surface consists of grain aggregates of about 100 to a few hundred nanometres in size (B). Each aggregate is composed of ultra-fine (several to a few tens of nanometres in diameter) grains (C). The red line traces are drawn to show the individual grain size. The SAED pattern indicates that the ultra-fine grains are randomly-oriented crystalline lime (D).
**Fig. S4.** Monitoring of CO$_2$ emission during the experiment conducted at the normal stress of 9.8 MPa and the slip rate of 0.17 m s$^{-1}$. The inset is the enlargement of the early stage of the experiment. The gray vertical bars indicate the first major emission timing of CO$_2$, considered the response time of Sensor 1, which seems to be simultaneous with the onset of weakening after the transient weakening and strengthening at the very early stage (< 7s).

**References**


