Earthquake lubrication and healing explained by amorphous nanosilica

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During earthquake propagation, geologic faults lose their strength, then strengthen as slip slows and stops. Many slip-weakening mechanisms are active in the upper-mid crust, but healing is not always well-explained. Here we show that the distinct structure and rate-dependent properties of amorphous nanopowder (not silica gel) formed by grinding of quartz can cause extreme strength loss at high slip rates. We propose a weakening and related strengthening mechanism that may act throughout the quartz-bearing continental crust. The action of two slip rate-dependent mechanisms offers a plausible explanation for the observed weakening: thermally-enhanced plasticity, and particulate flow aided by hydrodynamic lubrication. Rapid cooling of the particles causes rapid strengthening, and inter-particle bonds form at longer timescales. The timescales of these two processes correspond to the timescales of post-seismic healing observed in earthquakes. In natural faults, this nanopowder crystallizes to quartz over 10s–100s years, leaving veins which may be indistinguishable from common quartz veins.
lip weakening is fundamental to all earthquakes\(^1\), but there is no known universal mechanism for controlling the loss of rock strength\(^2,3\). The lack of positive heat flow anomalies around major continental faults suggests that the shear resistance on faults may be extremely low during displacement, but paradoxically, stresses near the faults may be high\(^4\). The proposal of “silica gel” lubrication, thought to cause extreme loss of shear resistance in high velocity friction experiments on quartz-rich rock, offered a tantalizing explanation for dramatic coseismic weakening which might apply

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**Results**

**Friction experiments.** Novaculite (chert) cores were acquired from Dan’s Whetstone Company, Percy, Arkansas, USA. The novaculite occurs in the whetstone quarry as cherty nodules within low-grade limestone. The novaculite consists of a porous aggregate of euhedral \(\sim 10\) \(\mu\)m quartz grains with traces of calcite and oxide minerals, and abundant fluid inclusions along grain boundaries and healed fractures. The friction experiments were conducted at the Department of Geosciences of the University of Padua, Italy, using the ROTary-Shear Apparatus ROSA. Two cylinders were sheared against each other at atmospheric humidity. After the experiment, the sample halves were recovered from the machine as one in order to preserve the wear material.

Shearing experiments were performed at equivalent velocities (as defined by \(^12\)) of 100 \(\mu\)m/s, 1 mm/s, 1 cm/s, and 10 cm/s at normal stresses of 2.5 MPa for total displacements of 3 m and 30 m (Table 1). Weakening was observed in every experiment, and most experiments achieved a steady state friction value after >0.3 m of slip. The friction coefficient evolved from \(0.7\) gradually to a steady state value of \(0.45–0.6\) in the 100 \(\mu\)m/s, 1 mm/s, and 1 cm/s experiments, and decreased dramatically to <0.1 in the 10 cm/s experiments (Fig. 1a).

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**Table 1 Summary of friction experiments and calculated temperature rise from FEM model**

| Sample run | Equivalent velocity (m/s) | Total slip (m) | Normal stress (MPa) | Bulk \(\Delta T\) (°C) from FEM model | Bulk \(\Delta T\) (°C) from half-space analytical solution | Peak \(\Delta T_{\text{flash}}\) (°C) |
|------------|--------------------------|---------------|--------------------|--------------------------------------|------------------------------------------------|--------------------------|
| 94 (failed)| 0.1 m/s in 10 s (velocity ramp) | 1 | 5 | - | - | - |
| 95* | 0.1 m/s in 2 s (velocity ramp) | 1 | 2.5 | - | - | - |
| 96 | 0.1 | 3 | 2.5 | 28.5 | 42.5 | 1006 |
| 97* | 0.1 | 3 | 2.5 | 23.6 | 45 | 1006 |
| 98* | 0.1 | 30 | 2.5 | - | - | 1006 |
| 99 | 0.1 | 3 | 2.5 | - | - | 1006 |
| 100 | 0.1 | 3 | 2.5 | - | - | 1006 |
| 101* | 0.1 | 3 | 2.5 | - | - | 1006 |
| 102* | 0.1 | 30 | 2.5 | - | - | 1006 |
| 110 (failed) | 0.001 | 3 | 2.5 | - | - | - |
| 111* | 0.001 | 3 | 2.5 | 38.0 | 60 | 318.2 |
| 112* | 0.0001 | 3 | 2.5 | 2.8 | 7 | 31.8 |
| 123* | 0.001 | 3 | 2.5 | 7.5 | 18 | 100.6 |

*denotes runs whose wear material was characterized in detail with one or more of TEM, SEM, FT-IR, and Raman Spectroscopy

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**Fig. 1** Results of friction and numerical experiments. a Coefficient of friction vs. displacement in novaculite friction experiments. b Temperature distribution from finite element model at the end of the experiments for fastest slip rate (10 cm/s, experiment 96) and c slower experiment (1 mm/s, experiment 123)
We estimated the bulk temperature rise of the slipping zone during the experiments using two methods: a finite element model with Comsol Multiphysics and a half-space analytical solution\(^3\). Fig. 1b, c show the geometry of the half-model, with novaculite in the center (density = 2750 kgm\(^{-3}\), thermal diffusivity = 5 m\(^2\)s\(^{-1}\), heat capacity = 0.75 × 10\(^{2}\) J (kg°C\(^{-1}\)); steel frame (density = 8000 kgm\(^{-3}\), thermal diffusivity = 16 m\(^2\)s\(^{-1}\), heat capacity = 0.5 × 10\(^{2}\) J (kg°C\(^{-1}\)), in contact with air (density = 0 kg/m\(^3\), thermal diffusivity = 1 m\(^2\)s\(^{-1}\), J (kg°C\(^{-1}\)). The Comsol model incorporated time-varying friction measured during the experiment as an input. Both approaches show average slipping zone temperature rises of ≤ 60° in every experiment (Table 1). We also estimated the peak temperature at asperities during flash heating using the approach of Violay et al.\(^{14}\) for a range of slip rates and asperity peak temperature at asperities during the experiment as an input.

Microstructure and composition of wear material. The starting material (novaculite) is composed mostly of ~10–50 μm quartz with trace amounts of calcite and has rough-walled pores about 100 μm in diameter (Fig. 3a). In all experiments, wear material on the sheared interface formed a ~5–30 μm-thick layer of <1 μm ellipsoidal particles (Fig. 3b, c, Fig. 4). High sphericity is characteristic of amorphous silica nanoparticles\(^{15}\), so rolling is not required to explain their shape. The particles form clusters up to 100–1000 nm across (Fig. 3) which explode under the electron beam, suggesting the presence of volatiles (Fig. 3c; compare to\(^{16}\)).

The nanopowder layer is cut by discrete slip surfaces ~1 μm thick (Fig. 3b, white arrows). When the novaculite cores are exposed, the sliding surface in plan view (Fig. 3c–f), the thin localized shears are revealed to be formed of discrete dense plates with smooth surfaces marked by slip-parallel striations, inter-layered within the nanopowder layer (Fig. 3e–f). We interpret these plates as the remnants of discrete slip surfaces. Fragments of plates are found in the inter-layer nanopowder (Fig. 3f), showing that development, breaking and reforming of striated plates occurred during a single experiment. The sliding surface of the novaculite underneath the wear material displays a shiny polish (Fig. 3d, ss). This polish is due to smoothing of the novaculite surface by initial abrasion, as well as by smearing and adhesion of nanopowder across the novaculite to fill surface pores. We observe no evidence of viscous fluids on the slip surfaces, so no evidence supports the formation of gel or melt during the experiments (consistent with\(^{9}\), cf.\(^{3}\)).

We used transmission electron microscopy (TEM) to examine the crystallinity and nanostructure of the wear material (Fig. 4). The nanopowder is predominantly composed of 100–1000 nm clumps of rounded to ellipsoidal amorphous nanoparticles, ~10–100 nm in diameter, and chips of quartz (Fig. 4, similar to\(^{9}\)). The relict quartz grains are larger (~1 μm; Fig. 4a, b, white arrows), and have stepped, fractured edges showing damage caused by comminution and frictional wear. The powder layer contains angular fragments of more densely packed particles (Fig. 4c) which correspond to the shiny striated plates (Fig. 3e–f).

At the sub-micron scale, it is clear that the sharp shiny plate is formed from gradational packing of the same amorphous nanoparticles, with increasing packing density toward the shiny slip surface (along white arrows in Fig. 4c). The fragments of broken slip surfaces are rotated relative to one another (as demonstrated by opposite directions of gradational packing in the two fragments of Fig. 4c), confirming that the slip surfaces formed and were broken up into fragments during sliding.

Raman spectroscopy was employed to characterize Si–O bonding in the nanopowder for comparison to crystalline and amorphous species of silica, and investigate the form of any water present. We used a 633 nm He–Ne excitation laser Raman microprobe spectrometer in the Materials Chemistry lab at McGill University. Spectra were collected from the powdered novaculite (starting material), the wear material, and a control nanosilica (a lab-made 2 μm nanosilica powder, Nyacol Nyasil 5; Fig. 5a). Shear-related structures were also interrogated without physical disturbance by using Confocal Raman microspectroscopy in situ (Fig. 6). Spectra were collected at evenly spaced points along transects from core to rim across the samples (Fig. 6).

The novaculite is an exact match for α-quartz\(^{17}\). The wear material spectra show a broad peak with weak structure in the region 100–600 cm\(^{-1}\) punctuated by sharp peaks due to minor contributions from E (phonon) and A1 modes in α-quartz from the exposed patches of novaculite beneath the wear layer (Fig. 3c, ss; Fig. 5a; Fig. 6). Compared with typical signatures of amorphous silica, the classic modes associated with oligomeric ring structures are absent in our wear material (red bands in Fig. 5a), indicating that a variety of Si–O species are present with no dominant modes (see Supplementary Discussion for additional description). The strong polarization-dependence across all wavelengths (Fig. 5a) indicates that the wear material displays anisotropy, perhaps related to the shear-parallel smearing observed in the striated plates and on the slip surface (Fig. 3d–e).

No silanol (Si–OH) or adsorbed water were observed by Raman (scans out to 4000 cm\(^{-1}\), not shown in Fig. 5a; \(^{18}\)). This spectrum is unlike previously published Raman spectra of glassy silica\(^{15}\) or commercial nanosilica we analyzed (see Supplementary Discussion for details). In summary, the nanosilica wear material formed by shearing of quartz-rich rocks is amorphous but anisotropic, is anhydrous within the detection limit of Raman spectroscopy, and has a unique Raman fingerprint, distinguishable from amorphous silica from other sources.

The quantity of wear material on the slip surface varied with slip rate (Fig. 6), for experiments with the same amount of slip (Table 1). Some wear material was ejected and lost during the
experiments and during sample unloading, so our observation is only qualitative. However, comparing Experiments 111 (1 cm/s) and 112 (100 µm/s) shows that more of the surface is covered with wear material and the layer is thicker in the faster experiment (Fig. 6). On sample 111, which displayed extreme weakening (Fig. 1), in situ Raman transects across the sliding surface shows quartz peaks across the center ~30% of the diameter, while amorphous wear material covers the outer ~70%, and the wear material is collected into dense smooth packs or plates which are concentrically smeared in the slip direction (Figs. 3, 6). On sample 112, which did not display substantial weakening (Fig. 1a), quartz peaks appear in the Raman transect in the center ~50% of the diameter, and in the outer rim of wear material, the powder is more evenly distributed. This observation of increased wear and amorphization at higher slip speeds is similar to previous experiments on clay-quartz mixtures.20

Fig. 3 Secondary electron images of microstructures in novaculite and wear material, collected with JEOL 8900 microprobe at McGill University (beam current = 20 kV). Images a and c–f are of experiment 97. Image b is of experiment 101. a Surface of unsheared novaculate (starting material) with empty (100 µm) pores. b Cross-sectional view of wear material layer. White arrows indicate thin slip zones composed of compressed powder. c View normal to slip surface (ss) that was opened by separating novaculate cores. Clumps of ellipsoidal powder grains decorate surface and adhere to striated slip surface. Uneven distribution of wear material leaves exposed patches of slip surface with remaining 10 µm pores. d Nanopowder (np) compressed into striated plates (sp) parallel to slip direction. e Broken fragments of striated plates, interlayered with nanopowder, displaying development and cataclasis of multiple slip surfaces during single shear experiment. f Closeup on wear powder showing quartz chips, 10 µm clumps, and 1 µm particles. Bright clusters show debris from clumps which exploded during observation.
In order to look for the presence of silanol (–Si–O–H), Fourier Transform Infrared (FT-IR) spectroscopy was collected using a PerkinElmer Spectrum TWO FT-IR instrument with a single-bounce diamond ATR crystal. The wear material displays FT-IR absorption band patterns distinct from both powdered novaculite (which matches α-quartz) and commercial amorphous nano-silica (Fig. 5b; Supplementary Note 1). The wear material spectra display features absent in the powdered novaculite, indicative of adsorbed H2O and silanol bending (Fig. 5b, Table 2), consistent with Hayashi et al., and the absorbances for stressed Si–O–Si bonds are more pronounced than in the powdered novaculite. We observe water and silanol in the FT-IR spectra, but no evidence of silanol or hydroxyl was detected in the Raman spectra. As the detection limits of the FT-IR are ∼10,000× lower than the Raman for hydroxyl and silanol, this result is consistent with a nanoparticle structure characterized by a thin hydrated silica layer rim surrounding an anhydrous amorphous silica core.

**Discussion**

We have shown that the lubricating wear material produced in moderate to fast slip rate experiments on novaculite consists of spherical nanoparticles of amorphous silica with hydrated surfaces. Quartz can be amorphosed by high isotropic pressures (~15–25 GPa), comminution in a mortar and pestle at room conditions, or shock pressurization. At similar normal load to our experiments (5 MPa), prepared quartz surfaces showed fractal distribution of contact size with an average contact stress on the order of 5 GPa, similar to the estimated contact stresses which generated amorphous wear material in previous experiments. It follows that the smaller contacts would experience stresses above the isotropic amorphization stress (~15–25 GPa) even under static loading conditions. Experiments on nanocrystalline silicon showed that pressure induced amorphization (at 19 GPa) produced meta-stable supercooled glass which persisted after depressurization, potentially analogous to production of our amorphous particles. It is not clear whether comminution causes amorphization due to creating highly variable stress conditions resulting in locally reaching the isotropic amorphization stress, or whether an additional mechanical or thermal effect lowers the amorphization threshold. In the case of comminution, high sphericity of wear particles appears to be a result of strain minimization in the material. Amorphous silicate has been produced in other experiments at lower slip rates and at lower slip rates with higher temperatures, without significant weakening, so it may be necessary for sufficient slip to form a continuous amorphous layer for weakening to occur.

Comparison of the wear material from experiments at different slip rates showed that the nanopowder was indistinguishable in

**Fig. 4** Transmission Electron Microscope images of wear material from experiment 101 (brightfield). a Quartz grain (Q) with rough fractured surface (white arrow). Clumps of amorphous silica particles (as) surround quartz grain. b Chips of crystalline quartz (top selected area electron diffraction pattern) and rounded clumps of amorphous particles (middle selected area electron diffraction pattern). At the scale of this image, nearly all amorphous silica grains are composites of smaller particles and fragments. c Broken fragments of striated plates composed of amorphous nanoparticles. Sharp slip surface composed of gradationally increasing packing density of particles toward slip surface (white arrows). Fragments are floating in loosely packed amorphous nanopowder. d Wear powder of rounded to elongate particles with grain size 10–100 nm that show no crystal structure (bottom selected area electron diffraction pattern).
The lack of discernible difference between the wear material formed in different experiments requires that the differences in shear resistance between the moderate slip rate (100 μm/s–1 cm/s) and fast slip rate (>1 cm/s) experiments (Fig. 1) must be explained by velocity-dependent properties, not just the presence of the wear material. The post-shearing strengthening is dependent on the evolution of material properties during the static hold periods, potentially by time-dependent bonding. We explain the rheological observations with two deformation mechanisms that cause weakening and re-strengthening on two different time-scales: particulate flow assisted by hydrodynamic lubrication; and intraparticle plasticity (Fig. 7). The action of these two weakening mechanisms together is akin to superplasticity sometimes described in crystalline materials which involves intraparticle deformation, as well as grain-boundary sliding between particles.

Although the amorphous wear material lacks long-range order, it is still dominated by silica tetrahedra, similar to crystalline species of silica. Si–O bonds which are dangling, stretched, bent (as shown in Fig. 5 and Table 2), or vacancies within and between silica tetrahedra all act as defects within the amorphous silica. Similar to crystalline materials, these defects are concentrated on particle surfaces. Variations in the Si–O bond angle in silica glasses (including stress-induced variations) cause changes in bulk moduli, solubility in acids, thermal expansion, viscosity, and rates of water diffusion in the glass. Any defect which concentrates stress within the amorphous material plays a role during deformation which is analogous to (and can be modeled as) a dislocation in a crystalline structure, although these ‘shear transformation zones’ are not geometrically similar to dislocations. The exceptional concentrations of defects and vacancies in amorphous silica nanoparticles encourage hydration and plasticity, especially at the small scales and high pressures as expected at asperity contacts (Fig. 7a). Yeo et al. have shown that heating, not just the presence of nanoparticles, is important for slip weakening. Hydration effects reduce the glass transition temperature and further promote plastic flow. The existence of the smeared nanoparticles forming the striated plates implies that the mild average frictional heating (Fig. 1b) experienced in the shearing experiments at 10 cm/s was sufficient to bring local patches above the glass transition temperature, allowing superplastic flow and the cohesion of wear powder to form the striated plates. The shear weakening effect would be reversed upon cooling, within seconds after the cessation of shearing.

Weakening in crystalline nanomaterials has been attributed to the activity of grain boundary sliding, but amorphous nanoparticles do not contain crystalline grain boundaries, and could even be work-hardening due to the rapid development of dislocation tangles. Therefore, we invoke a superplastic flow mechanism in our amorphous nanopowders, but the details of the contributing mechanisms may be different than in crystalline wear powders. In amorphous silica, the mechanism of bulk flow is by silicon-oxygen bond switching and void migration, which can
Fig. 6 Photos of shear surfaces and corresponding Raman spectra transects. a Sample 111 (1 cm/s), and b Sample 112 (100 µm/s), showing discontinuous concentric rings of powder on sample surface. Raman spectra from transect scans are shown for each sample (c corresponds to sample 111, d corresponds to sample 112). The appearance and disappearance of the sharp quartz peaks along the transect can be correlated to the amount of visible wear material in the photos. See text for additional discussion.

### Table 2 Peak positions in the FT-IR spectra and their corresponding vibrational modes

| Vibrational mode                      | Position of peak (cm⁻¹) |
|---------------------------------------|--------------------------|
|                                       | Nanosilica               | Commercial nanosilica (this study) | Wear material (this study) | Powdered novaculite (this study) | α-quartz          |
| Isolated (free) silanol[^66]          | 3747                     | 3745                               |                            |                            |                  |
| H-bonded silanol[^66]                 | 3660                     | 3650                               |                            |                            |                  |
| Stretching of H₂O[^66]                | 3450                     | 3348                               | 3424                       | 1087, 1043                 | 1175, 1100       |
| Asymmetric stretching of Si-O-Si[^20] | 1089                     | 1066                               | 1052                       |                            |                  |
| Bending of Si-OH[^67]                 | 972                      | 1066                               | 797, 780 (double peak)     | 795, 776 (double peak)     | 797, 778 (double peak) |
| Symmetric stretching of Si-O-Si[^20,68]| 812                      | 798                                |                            |                            |                  |
| Symmetric bending of Si-O-Si[^20]     |                           | 695                                |                            | 694                        | 695               |
| Asymmetric bending of O-Si-O[^20]     | 474                      | 539 (shoulder), 452                | 515 (shoulder), 447        | 510 (shoulder), 446        | 516 (shoulder), 470 |
change the number of atoms in oligomeric rings39, and may explain the lack of any preferred coordination number in our amorphous silica wear material (Fig. 5a).

Simultaneous with intraparticle plastic deformation, hydrated particle surfaces cause a second mechanism of slip weakening (Fig. 7b, 40,41). Hydration is particularly effective in stressed Si–O bonds on fresh surfaces42, forming silanol films that trap water layers of unknown thickness between the particles42,43, enabling hydrodynamic lubrication. Hydrated silica surfaces exhibit hydrophilic and hydrophobic regions, depending on silanol density44, which create areas of interparticle repulsion and water adsorption. Hydrated surfaces on amorphous silica show a significant lubrication effect, which increases in magnitude with shearing velocity, particularly at high-stress and frictional contacts, where the increased pressure accentuates surface hydration40,45.

Post-slip healing is caused by the reversal of the same mechanisms which cause the weakening. The hydrated surfaces are particularly favorable to inter-particle bonding when the relative motion ceases. In static contact with one another, the silanol groups rearrange to construct a silica tetrahedron (siloxane), binding the particle surfaces together, and releasing a molecule of water46. The timescale of this bonding depends on contact aging, so the strength of the bond is time-dependent. This effect may explain instantaneous weakening upon re-shearing, as well as re-strengthening on ~10 s timescales observed by Goldsby and Tullis5. We found evidence for this surface bonding in the agglomeration of particle clusters (Fig. 3c) that explode under the electron beam, showing that vaporization of the surface-bound water will disaggregate them. These are equivalent to Togo and Shimamoto’s47 finding of sintering between quartz gouge grains in high velocity experiments and the formation of shiny slip surfaces in experiments similar to ours, but they did not test for the presence of amorphous silica which we observe forming these features.

Our experiments were modeled after those which first reported silica gel5,6, but we have documented that the wear material produced in our experiments, which display the same weakening behavior, is not gel. Both the previous experiments5,6 and our experiments produced nanopowders48 and display similar weakening behaviors, but our experiments did not produce gel, perhaps due to different conditions. We therefore prefer the interpretation that the wear powder is likely responsible for the weakening behavior in both sets of experiments. Our results show that the behavior of hydrous amorphous silica nanoparticles at seismic slip rates can explain both the slip weakening and time-dependent recovery in laboratory experiments. The similarity of the wear material formed at all tested slip rates shows that the mere presence of amorphous silica nanoparticles is not enough to cause the observed drastic weakening. The whole range of tested velocities (100 µm/s–10 cm/s) are unique to earthquakes49, but the lubrication only occurred at slip velocities >1 cm/s. Due to the strong velocity weakening effect, the formation of this material likely promotes runaway slip. These fast slip rates are necessary to refresh interparticle contacts (preventing silica bonding) and to warm or pressurize44 the interior of the amorphous particles above the glass transition. The wear material productivity was higher in the experiments which display this weakening, suggesting that a continuous layer of >10 µm thickness is required to activate silica weakening, c.f.5,8,16. Therefore, the formation of amorphous silica nanopowder might facilitate earthquake slip through mild weakening at small offsets or low seismic slip rates, and the extreme weakening (friction coefficient < 0.1) at peak slip rate could potentially result in complete stress drop on the affected portion of earthquake rupture surfaces. As real earthquake faults are rough50, the work done in frictional heating and amorphization is not uniform across natural slip surfaces. Compared to these experiments, a natural fault might require more or faster slip in order to build up a wear material layer of sufficient thickness to cause catastrophic weakening e.g.51. Or, a continuous layer may never develop, resulting in some residual strength on the fault, and preventing complete stress drop during earthquakes, e.g.52. Although discrete sliding surfaces developed in patches during the experiments, they were broken and refreshed during sliding, and no through-going principal slip surface or zone was found in our samples, including those that showed extreme weakening (Fig. 3b). One possible explanation is that the polished fragments lie at a slight angle to the slip plane, as they appear to be shingled with the forward edge (upper right in Fig. 3e and f) appearing to onlap the leeward edge of the neighboring fragment. It is unclear whether they formed in this orientation or were inclined due to drag of the opposite fault wall, but this pattern would prevent these slip surfaces from smoothly linking up to form a continuous shear surface across the whole sample.

Amorphous silica will crystallize to quartz within a few years at typical crustal temperatures53, with crystallization rates enhanced by the presence of hydroxyl or other impurities and by differential stress54. Thin, translucent, nano-crystalline to micro-crystalline quartz layers have been reported on natural fault surfaces, containing patches of amorphous silica, and relic silica nanoparticles entombed in strain-free quartz crystals55–57. These continuous coatings of amorphous silica or cryptocrystalline quartz on natural fault surfaces may constitute the rock record of silica lubrication in past earthquakes.

**Methods**

**Friction experiments.** Experiments were performed using the ROtary-Shear Apparatus ROSA (built by MARUI & CO., LTD (model MIS-233-1-77) as designed...
Facility, University of New Brunswick. Adobe Photoshop was used to adjust the Transmission Electron Microscope (STEM) at the Microscopy and Microanalysis Facility. Transmission electron microscopy (TEM) images and Scanning Electron Microscope at the University of New Brunswick Microscopy and Microanalysis Laboratory were collected by J.C. White using the JEOL 6400 McB. Figure 2 was collected by C. Rowe on the JEOL 8900 microprobe in the Earth and Planetary Sciences Department at McGill University. Figure 2b was collected by J.C. White using the JEOL 6400 Scanning Electron Microscope at the University of New Brunswick Microscopy and Microanalysis Facility. Transmission electron microscopy (TEM) images and diffraction patterns were collected by J.C. White using the JEOL 2011 Scanning Transmission Electron Microscope (STEM) at the Microscopy and Microanalysis Facility, University of New Brunswick. Adobe Photoshop was used to adjust brightness and contrast of the backscattered electron and transmission electron images.

Raman spectroscopy and polarizability experiments. Raman spectra were collected by K. Lamothe using the laser Raman microprobe spectrometer with 633 nm He–Ne excitation laser in the Materials Chemistry lab at McGill University.

Polarizability experiments have shown that the wear material is highly polarization dependent (Fig. 3a). The R-band shows a strong polarization dependence for parallel (XX), 220° versus the perpendicular (XYY, YXY), 0° polarizations (Supplementary Fig. 4). The Z-axis refers to the axis along which the incident laser beam propagates to the sample and the scattered photons return (incident electric field). The X-axis refers to the horizontal axis for the sample, generally parallel to the front of the stage on which the sample is mounted, and Y is in the plane of the stage, perpendicular to the X-axis. Notation for polarizability experiments is given in the form of a(bcd) where a is the axis along which the incident laser propagates, b is the axis of polarization of the incident laser by the polarizer, c is the axis of polarization of the scattered photons by the analyzer, and d is the axis of propagation of the scattered photons (Supplementary Fig. 1).

Data availability

The Matlab codes used for temperature calculations including Fig. 1b are archived on GitHub at https://github.com/aretu/thermalmatlabcodes. All data is available from the authors on request.

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Post-experiment sample preparation and observation. Following sliding experiments at Padova, samples were recovered intact from the shearing apparatus, secured and sealed with tape, and sent to McGill University. Some samples were cut longitudinally (along the core axis) in order to image the sliding surface and wear material in cross section (e.g., Fig. 3a, Fig. 4). Some samples were gently cut longitudinally (along the core axis) in order to image the sliding surface and wear material in cross section (e.g., Fig. 3a, Fig. 4). We used the peak friction coefficient (μ = 0.7) to calculate the heating, so actual asperity temperatures were lower once weakening began.

The properties of the wear material are poorly constrained, so we chose values conservatively to place a maximum bound on the flash heating temperature at asperities. The temperature was calculated using the properties of water-poor petrographic type 1 silica glass (density ρ = 2200 kg m⁻³, heat capacity c = 1026 kg⁻¹k⁻¹), and thermal diffusivity α = 0.7 m² s⁻¹) 39, 40 μ as our peak friction coefficient (μ = 0.7), V is our slip rate (v = 0.0001–0.1 m s⁻¹), and t s is contact time. Contact time is related to the radius of circular asperities a and slip rate V as:

$$t_s = \frac{a}{V}$$

The radius of the asperities is related to the normal force F = 1227 N and Pm, the indentation strength of the sample:

$$a = \sqrt{\frac{F}{P_m M}}$$

Backscattered electron images (Fig. 2, except for 2b) were collected by C. Rowe on the JEOL 8900 microprobe in the Earth and Planetary Sciences Department at McGill University. Figure 2b was collected by J.C. White using the JEOL 6400 Scanning Electron Microscope at the University of New Brunswick Microscopy and Microanalysis Facility.
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