and temperature on the electrical conductivity of wadsleyite and ringwoodite. Owing to the small activation enthalpy, the temperature effect is relatively small: a variation in temperature of $\sim 200\,\mathrm{K}$ results in a change in conductivity of a factor of ~ 2. In contrast, the expected water contents in the transition zone range from almost dry ($\sim 10^{-4}\,\mathrm{wt\%}$) to water-saturated ($\sim 3\,\mathrm{wt\%}$), which corresponds to the variation of conductivity by a factor of $\sim 10^{3}$. Therefore water content is well-constrained by the conductivity data.

The electrical conductivity in the transition zone ranges from $\sim 10^{-2}\,\mathrm{S\,m^{-1}}$ to $\sim 1\,\mathrm{S\,m^{-1}}$ (refs 5–7). This corresponds to water contents of ~ 0.001 to $\sim 0.4\,\mathrm{wt\%}$. For the upper mantle of the North Pacific Ocean, where a detailed inversion was made using mineral physics constraints[5], the conductivity in the transition zone is $\sim 10^{-1}$ to $\sim 5 \times 10^{-1}\,\mathrm{S\,m^{-1}}$ and the corresponding water content in the transition zone is estimated to be ~ 0.1–$0.2\,\mathrm{wt\%}$ for the temperature range of 1,825–1,900 K (Fig. 3). The estimated water content in the north Pacific transition zone (~ 0.1–$0.2\,\mathrm{wt\%}$) is significantly higher than the estimated water content in the upper mantle[8,9] and probably exceeds a critical concentration for partial melting. This suggests that there is a marked layering in water content in the Earth's mantle. This is consistent with a recent model of material circulation[4] involving the separation of the circulation of incompatible elements from that of major elements near 410 km, but is not consistent with a model involving vertical circulation of hydrogen together with major minerals. However, some regional variation in electrical conductivity was also reported[5,6], suggesting a large regional variation in hydrogen content (and temperature) in the transition zone. □

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Particle size and energetics of gouge from earthquake rupture zones

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Grain size reduction and gouge formation are found to be ubiquitous in brittle faults at all scales[1–4], and most slip along mature faults is observed to have been localized within gouge zones[5,6]. This fine-grain gouge is thought to control earthquake instability[3,6–8], and thus understanding its properties is central to an understanding of the earthquake process[7,9]. Here we show that gouge from the San Andreas fault, California, with $\sim 160\,\mathrm{km}$ slip, and the rupture zone of a recent earthquake in a South African mine with only $\sim 0.4\,\mathrm{m}$ slip, display similar characteristics, in that ultrafine grains approach the nanometre scale, gouge surface areas approach $80\,\mathrm{m^2\,g^{-1}}$, and grain size distribution is non-fractal. These observations challenge the common perception that gouge texture is fractal[10,11] and that gouge surface energy is a negligible contributor to the earthquake energy budget[3,9,12]. We propose that the observed fine-grain gouge is not related to quasi-static cumulative slip, but is instead formed by dynamic rock pulverization during the propagation of a single earthquake.

Gouge formation is commonly attributed to wear and attrition of sliding surfaces[1–3,5,7] or to implosive loading[13] during earthquakes. Models of wear and attrition[10] predict that progressive shear within gouge zones should lead to grain size reduction due to amplified stresses at grain contacts, and to fractal particle size distributions[10] of the gouge; these predictions are supported by field and experimental observations[1,2,10,11] with a few exceptions[2].

However, there are two main pitfalls in standard textural analysis of fine-grained gouge[14]. First, optical microscopic analysis and mechanical sieving are restricted to grains a few micrometres in diameter or larger. Second, measurements of the size distribution and surface area of fine-grained materials are susceptible to erroneous results due to the aggregation or agglomeration of extremely fine particles[15]. For example, our preliminary measurements of the particle size distribution (PSD) of fault gouge with a laser particle-size analyser reveal profound time drift: the mean grain size of pulverized granite from the San Andreas fault zone (see below) decreased by $26 \pm 13\%$ (s.d.) during 0.5 h of continuous measurement (on the basis of 145 samples[16]). This time drift reflects disaggregation into primary grains, as is known for clay mineral aggregates[17]. Questions therefore remain open with regard to the size, PSD and surface area of primary particles in fault gouge. To determine these properties accurately we developed a new pro-

cedure of continuous measurements (see Methods). The range of measured particles, down to grains tens of nanometres in size, are also observed directly by scanning electron microscopy.

Pristine gouge is difficult to find. Chemical alteration and lithification alter the texture in exhumed fault zones[18], gouge found at surface rupture zones cannot reflect mechanical conditions at depth, and rupture zones are usually inaccessible at earthquake focal depths. We chose two fault systems that partly remove these limitations. The first is the San Andreas fault, which is a system 1,200 km long that accommodates hundreds of kilometres of right-lateral slip. The better-known exposures of deep parts of the San Andreas fault are inactive segments in southern California that were uplifted from 2–4 km depth[5,6,18]. Our study focuses on San Andreas gouge exposed in the Tejon Pass region[19] (~100 km north of Los Angeles), alongside the rupture zone of the $M = 8.0$ earthquake in 1857 (Fig. 1a). Here, three sub-parallel fault segments bound a gouge zone 70–100 m wide composed of pervasively pulverized granite[19], distinctly different in PSD and morphology from weathered granites outside the fault zone[19]. On the basis of current uplift rates along the San Andreas system[20], we estimate that the Tejon Pass region has experienced as much as 4–6 km of uplift since the Pliocene epoch, and that the observed gouge formed at this estimated depth.

South African gold mines, 1.0–3.5 km deep, are shaken daily by thousands of earthquakes. The mines provide access to rupture zones of these earthquakes at focal depth, a unique opportunity for earthquake investigations[4,21,22]. Gouge is analysed from the rupture zone of the 1997 $M = 3.7$ earthquake in the Hartebeestfontein gold mine (~120 km southwest of Johannesburg, South Africa). This event occurred within unfaulted quartzitic layers at ~2 km depth and produced a new fault (the Bosman fault) later uncovered by mining operations. The Bosman fault zone is at least 5 m wide and 100 m long with 0.37 m of maximum dip-slip displacement, and contains four to six large subparallel segments with hundreds of secondary small fractures (Fig. 1b). Fractures are filled with white gouge that is commonly observed in brittle failure zones of quartzite in mines[23]. The gouge of the newborn Bosman fault formed from a single earthquake and was not affected by cumulative slip of multiple seismic events.

The present study includes PSD measurements of ~250 gouge samples from both faults; 155 samples were measured for 0.5 h or more, with eight samples being measured for 45–190 h (see Methods). The results are shown by the following: first, the initial and final PSD (after 72 and 190 h) of the gouge (Fig. 2a); second, the initial and final cumulative frequencies of grain numbers (Fig. 2b); and third, the power-law time decay of mean grain size and the associated increase in surface area of gouge from both faults (Fig. 3). Because the results for the long-duration measurements are generally similar, the figures show only representative samples.

We determined geometric surface area from the PSD of the gouge first by assuming smooth, spherical grains. Independently, the surface areas of six untreated samples of San Andreas gouge were measured with the Barrett–Emmett–Teller (BET) N_2 adsorption technique[15]. To estimate grain roughness, we calculated $\lambda =$ (BET surface area)/(geometric surface area); the λ value, 6.6 ± 1.5, for these samples is similar to a known range of λ of 5.5–22 (ref. 24). With the use of $\lambda = 6.6$, the calculated geometric surface area is converted to equivalent BET surface area (Fig. 3b), revealing surface area values as high as 80 m^2 g^{-1}. This surface area is probably a conservative estimate because grain disaggregation does not reach asymptotic values by the end of the long runs (Fig. 3). Scanning electron microscope images of gouge aggregates can also be used to estimate surface area (in m^2 g^{-1}) of roughly cubic fragments as ~$2/L$, where L is the grain size in micrometres. Thus, fragments of 0.02 μm of aggregated gouge (Fig. 4) correspond to a surface area of ~100 m^2 g^{-1}.

Inspection of Figs 2 and 3 reveals the following three properties. First, gouge PSD from both faults varies profoundly with run time, changing from an initial range of 0.04–200 μm to less than 1 μm after 72–190 h (Fig. 2a). The mean grain size does not attain asymptotic values (Fig. 3a), indicating that primary grains, which are tens of nanometres in size, might stay aggregated even after long runs. Accordingly, the apparent surface area of gouge grains increases with time and the power-law trend indicates a surface area of 100 m^2 g^{-1} after 300–500 h (Fig. 3b).

Second, gouge samples from the two faults display similar behaviour and final PSD even though the two faults are from strikingly different settings and magnitude.

Third, the grain number–size distribution of disaggregated gouge does not fit a systematic fractal distribution (Fig. 2b) because different slopes (corresponding to different fractal dimensions) are attained with progressive disaggregation. It is therefore inferred that the commonly observed fractal PSD[1,2,10,11] reflects aggregated gouge grains in a restricted range of coarser grain sizes.

These results permit a better estimation of the earthquake energy balance. The gouge surface area of ~80 m^2 g^{-1} (Fig. 3b) corre-
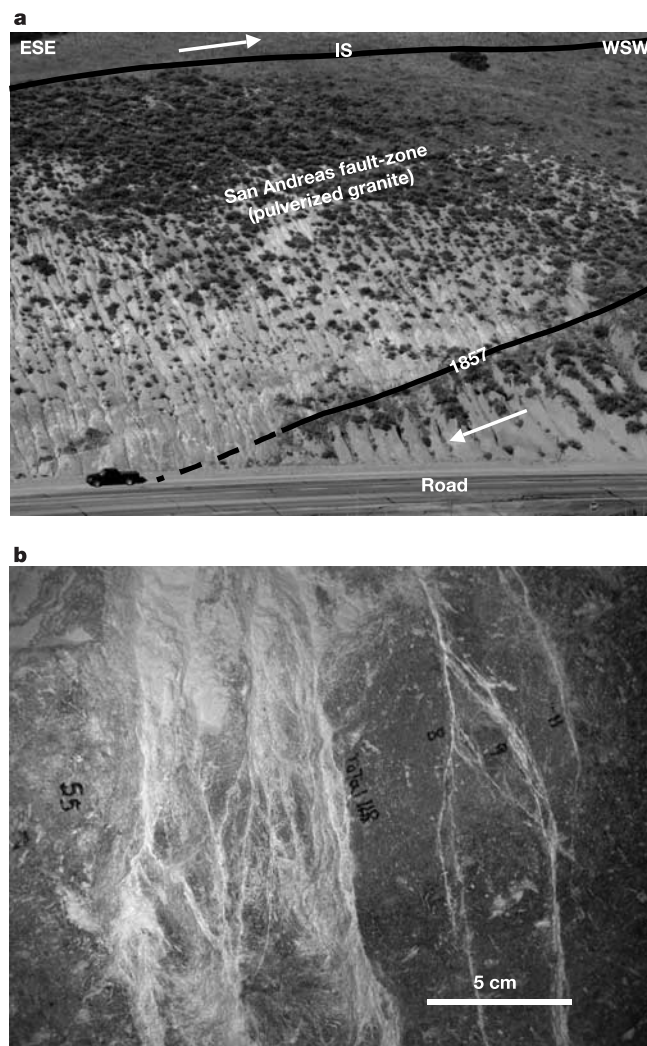

Figure 1 Field setting of the investigated faults. **a**, The San Andreas fault-zone at Tejon Pass, California. The car is shown for scale. IS, inactive fault segment; 1857, slipping segment of the 1857 earthquake. Note the gouge zone 70–100 m wide with badland morphology of the pulverized granite. This exposure and its extensions were mapped, and hundreds of gouge samples were collected. **b**, Close-up view of the fractured zone of the Bosman fault (text). The white striations are coalescing fractures filled with gouge powder (rock flour) that cut across the solid, dark quartzite.

sponds to a surface energy of 0.2–0.36 MJ per m² of the fault surface for a gouge zone 1 mm thick (for a specific surface energy of quartz of 1–1.8 J m⁻²). The Bosman fault earthquake generated tens of subparallel fractures that are each ~1 mm thick and filled with gouge (Fig. 1b); summation of the surface energy, marked here by U_s, of 10–30 fractures yields $U_s \approx 3$–10 MJ m⁻². This value is roughly equal to the frictional energy calculated for the Bosman earthquake, $U_f = \tau d \approx 8$–12 MJ m⁻² (τ is the estimated shear stress and d is the measured slip) and it is also similar to the energy release rate of earthquakes of 0.5–5 MJ m⁻² (ref. 25) to 1–100 MJ m⁻² (ref. 26). These energy relations suggest that the surface energy consumed by new gouge that forms during an earthquake can account for 50% or more of earthquake energy.

Finally, we conclude that the observed fine-grained gouge did not form by quasi-static wear and attrition, but rather formed by dynamic rock pulverization during earthquake propagation. This conclusion is based on two outcomes of the analysis. First, the similarity between the PSD of San Andreas gouge with ~160 km of slip at Tejon Pass, and the PSD of the Bosman fault gouge formed by one earthquake with 0.37 m slip, clearly indicates a lack of correlation between slip amount and grain size. Further, because a single earthquake generates the fine-grain gouge, it seems that the governing parameters of gouge formation are earthquake processes and not the cumulative slip attrition. Second, there is an apparent difference between energy consumption by gouge formation during an earthquake (for example the Bosman fault) and during wear in quasi-static experiments²⁷. In the former, gouge formation consumed ~50% of the earthquake energy (see above), whereas in the latter, gouge formation consumed only 0.2–0.3% of the supplied mechanical energy (we calculate from ref. 27 that $U_f \sim 7$ MJ m⁻² and $U_s \sim 1.5 \times 10^4$ J m⁻², by assuming that their experimental gouge has the same surface area as that in the Bosman fault). An earthquake can pulverize rocks by a few mechanisms: one is the sequence of fault-normal unloading followed by implosive loading during the earthquake passage¹³; another results from the deformation conditions at the tip of the earthquake rupture²⁸. We calculated a maximum tension of ~5 GPa and dilation rates of ~3 × 10⁵ s⁻¹ at the tip of a mode II fracture propagating at 80% of the shear wave velocity²⁸; these intense conditions are comparable to shock loading²⁹ and could pulverize rocks into gouge.

We now apply the proposed dynamic rock pulverization to the San Andreas fault. If each earthquake in the studied area (Fig. 1a) generated a gouge zone 10 mm thick with ~80 m² g⁻¹ (Fig. 3b), the corresponding surface energy would be 2.0–3.6 MJ m⁻² for each
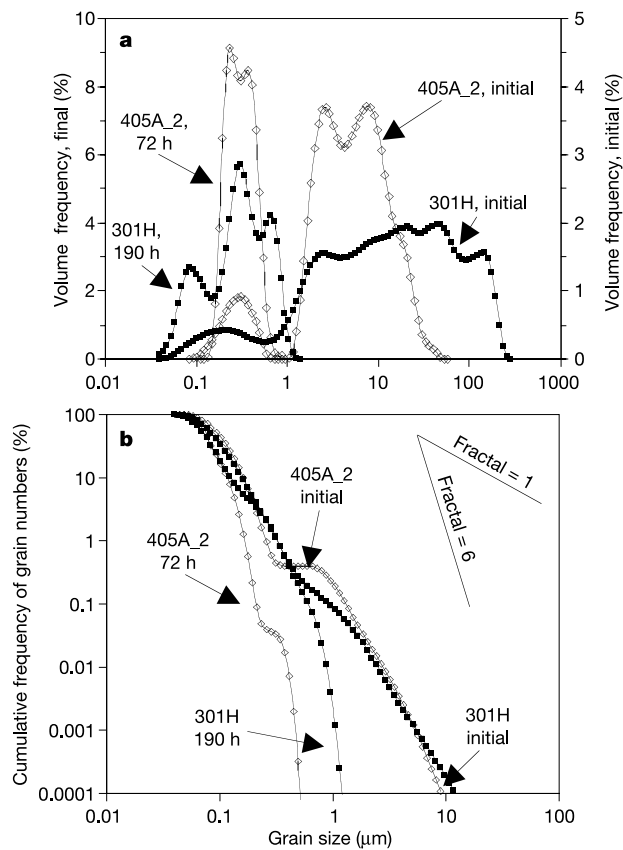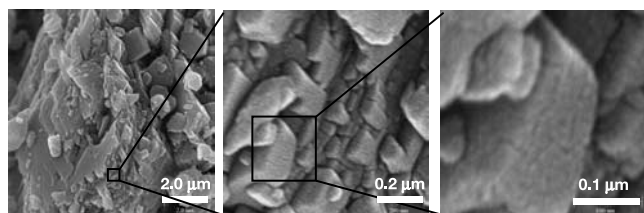

Figure 2 ...

Figure 3 ...

Figure 4 Scanning electron microscope images of untreated gouge from San Andreas gouge, with an order-of-magnitude resolution increase from left to right. The gouge samples were mounted onto colloidal graphite coating covering upper portions of platinum trays, and sputter-coated with gold–palladium under vacuum. Note the particles of 0.02–0.05 μm in the middle and right frames.

event. In such a case, the observed gouge zone 70–100 m wide was formed by 7,000–10,000 earthquakes, which is in agreement with estimates of recurrence intervals. Although the present observations on gouge energetics are in accord with some studies[30], they contradict common thought that gouge surface energy is a negligible component of earthquake energy balance[3,9]. If our conclusions are valid in general, they could explain, for example, the heat flow anomaly of the San Andreas fault system[6]. □

Methods

We employ a Beckman Coulter LS230 laser diffraction particle size analyser. Its 750-nm laser source and proprietary polarization intensity differential scattering (PIDS) technology provide detection limits of 0.04–2,000 μm. Spectrometry by laser diffraction does not discern between primary particles and agglomerates and is therefore sensitive to the degree of agglomeration inside the analyser[14,17]. Disaggregation is a time-dependent process that can occur over the course of days in silicate mineral suspensions[17]. Accordingly, gouge PSD measurements lasting up to 190 h were taken, during which progressive disaggregation could be discerned (Figs 2, 3). Initial sonication accelerated disaggregation but had no noticeable influence on the final PSD. Ultrafine particles might reagglomerate during the analysis[14], as indicated by the increased scatter in surface area at long times (Fig. 3b). Power-law disaggregation (Fig. 3) and recurring agglomeration/disaggregation during analysis indicates that PSD and surface area results are conservative estimates of primary gouge particle size and area produced by the seismic slip. Ultrafine particles could also have been lost as a result of Ostwald ripening and volatilization during sampling and handling.

The collected gouge samples were sealed at the site and stored in plastic bags. For the PSD measurements, tens of micrograms of sample were added to 25 ml of an aqueous surfactant solution (usually 1% analytical reagent grade sodium metaphosphate prepared with doubly distilled water) or methanol and then subjected for 30 min to a low-energy sonic bath. After an additional 30 min this slurry was added to the laser analyser containing 125 ml of the same solution. Measurements of the diffraction spectrum were performed with continuous circulation inside the analyser, and PIDS was used in all reported runs. Spectral analysis was performed with proprietary software using the Mie scattering model[14], with constants for the complex refractive index plus wavelength dependence for quartz[14] and an absorption coefficient of 0.01.

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New material of the earliest hominid from the Upper Miocene of Chad

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Discoveries in Chad by the Mission Paléoanthropologique Franco-Tchadienne have substantially changed our understanding of early human evolution in Africa[1–3]. In particular, the TM 266 locality in the Toros-Menalla fossiliferous area yielded a nearly complete cranium (TM 266-01-60-1), a mandible, and several isolated teeth assigned to *Sahelanthropus tchadensis*[3] and biochronologically dated to the late Miocene epoch (about 7 million years ago). Despite the relative completeness of the TM 266 cranium, there has been some controversy about its morphology and its status in the hominid clade[4,5]. Here we describe new dental and mandibular specimens from three Toros-Menalla (Chad) fossiliferous localities (TM 247, TM 266 and TM 292) of