

REPLY TO COMMENTS BY REVIEWER #1 SE-2020-85

Below we pasted the reviewers' comments, with in red our reply to each comment made. Where applicable we indicate how/ where a comment has been addressed by referring to line and figure numbers in the revised manuscript (ms).

Anonymous Referee #1

Received and published: 13 July 2020

Dear Editor, I have reviewed the paper entitled "The physics of fault friction: insight from experiments on simulated gouges at low shearing velocities" by Verberne et al., as a potential article to be published in Solid Earth. I start by saying that this is a review article and does not contain any new results. The authors summarize a vast amount of work that has been carried out in the last 20 years or more at the Utrecht University rock mechanics laboratory. The main focus of this review is to give the reader a general overview of the development, and the current state-of-the-art, including strengths and limitations, of the CNS (Chen-Niemeijer-Spiers) microphysical model for fault friction and the earthquake cycle that is based on experimental evidences derived from experiments performed at the Utrecht laboratory. The review is well organized, in fact the authors start by clearly describe the experimental facilities used to perform the experiments, then they summarize some case studies that have put the basis for the formulation of CNS model. Afterwards, they describe the theoretical foundation of the model validating it with a comparison with the experimental data. Finally, they discuss the CNS model as applied to earthquakes simulation with a comparison with Rate and State- Friction (RSF) constitutive equations that is the most used framework so far. Throughout the review, the authors make the appropriate references to direct the reader to the relevant papers that have been published regarding the various aspect of the development of the CNS model. The papers are all in very good journals and highly cited so that the scientific basis for this model is not under discussion. In general the paper is very well written and organized and the figures are appropriate and it represent a necessary step to summarize the work done in developing this model. For these reasons I recommend publication after the authors address some minor concerns as listed below.

We thank the reviewer for his/her constructive review, which has helped to improve the quality of the ms.

Comments to the authors:

General: A minor aspect, but it should absolutely improve, regards the figures. From figure 3 throughout figure 10, they look like screen shots taken from the cited articles. This is true to the point that in figure 3 is impossible to read the text in the different figure panels. I strongly recommend the authors to produce high quality figures.

We fully agree that the figure quality in the .pdf version of the submitted ms was inadequate. We suspect that this may have occurred upon rendering a merged version of the ms. To ensure the best quality figures in the final manuscript, each figure as been re-exported from their original format (.ai or .cdr) to .jpg format, at 300 DPI resolution. In addition, we have increased the overall quality of each figure by adjusting text within, adopting a uniform style (font type, size, etc.), and by improving the figure captions.

I think that one aspect that should be improved in this review, since in the single papers cited is poorly addressed, is the relation between the CNS model and its physical basis with the interpretation of the mechanical work related to dilation as it was developed by Marone et al., 1990 JGR and Beeler et al., 1996 JGR. In particular they interpret the velocity dependence of friction (v-strengthening or weakening) based on an energy balance of the work done against

the normal stress (i.e. dilation rate) and relate it with the degree of shear localization. This basis are very similar to the CNS model. However, something that is not very clear to me is that in the observations of Marone and Beeler velocity perturbations that lead to fault dilation are associated with velocity strengthening frictional behavior, and shear localization is associated with velocity weakening behavior. While in the CNS model increasing in porosity leads to velocity weakening and “localization” by ductile mechanisms to velocity strengthening. Those experiments were conducted on crystalline material such as quartz or granite and the CNS model was developed for calcite that notably undergoes IPS. Can the authors implement some comments about these models?

This is an interesting point raised by the reviewer, which we are happy to discuss. The interpretation of the mechanisms controlling fault gouge shear deformation offered by Marone et al. (1990) and Beeler et al. (1996) is rooted in observations of fault strength, velocity dependence, and dilatation, from experiments on simulated quartz(-rich) gouges. The correlations between the data reported are intriguing indeed, and the interpretations offered stimulating -as recognized from the important work that was directly or indirectly inspired by it (see e.g., Segall and Rice, 1995; Scruggs and Tullis, 1998; Sleep et al., 2000; Samuelson et al., 2009). However, the Marone/ Beeler model is based on an intuitive assumption or hypothesis, which, while inspiring and broadly consistent with trends seen in their experimental data, has no explicit physical or thermodynamic origin.

Quoting Beeler et al. (1996), “*Marone et al. [1990] hypothesized that the friction velocity dependence of simulated gouge is the sum of the friction velocity dependence of bare surfaces and the velocity dependence of dilation rate*”. The CNS model re-evaluates the role of contact friction and dilation, using an established energy balance approach. In effect, the CNS model assumes that gouge shear resistance is caused by energy consumed in driving i) grain boundary friction (equivalent to ‘bare surface friction’ of Marone et al.) and ii) dilatation. However, net (i.e. measured) dilatation, constant in the case of steady-state sliding, is the result of competition between porosity increase caused by rate-insensitive granular flow (characterised by a dilatancy angle) and intergranular compaction by time-dependent creep processes (such as IPS mentioned by the reviewer - though the same principles apply for any creep mechanism). In the Marone/ Beeler model, intergranular creep processes are ignored, which means that dilatation is artificially assumed to be shear rate dependent and always leads to an increase in porosity. If this increase occurs faster than the rate at which pore fluid can flow in, the pore fluid pressure will decrease, leading to an increase in effective normal stress and so-called ‘dilatancy strengthening’ (Segall and Rice, 1995; Samuelson et al., 2009). While the latter is relevant especially in the case of transients, micro- and nanostructural observations, as well as compaction phenomena occurring during slide-hold-slide experiments, for example, clearly demonstrate an important role of creep mechanisms in friction experiments, suggesting that their incorporation in models for shear of gouge-filled faults represents a key step towards capturing physical reality.

Regarding the inferred relation between shear strain localization and velocity weakening behaviour, we further note that there is little microstructural evidence of any systematic nature to support this. When examined with a microscope, sheared gouges usually show a localized shear band structure regardless whether the mechanical data implies velocity strengthening or -weakening behaviour (see Verberne et al., 2013, 2015, 2019; Niemeijer, 2018). However, in view of the major differences between our experiments and those of Marone/Beeler and co-workers (i.e., materials investigated, P-T- $\dot{\gamma}$ conditions employed), it is perhaps not realistic to expect full agreement of the results. More work is needed on fault gouge microstructure development and its relation with sliding velocity, normal stress, and displacement. Until this is clarified, care should be taken when interpreting a relation between fault mechanical properties and gouge microstructure.

To address the reviewers' comment, in the revised ms we now include a brief statement on the important findings regarding the role of dilatation reported by Marone et al. (1990), and on the subsequent modelling work that was derived from it (lines 138-142). While we acknowledge the seminal impact of the work by Marone et al (1990) and Beeler et al al (1996), we feel that a detailed comparison with the CNS model would be too lengthy to include in the present ms

Specific:

L39: "Seismic fault motion of this type" it is not very clear to me. The authors refer to many fault slip styles in the previous sentence, so I would rephrase maybe with "the full spectrum of slip behaviors".

OK. We were referring to 'slow slip and earthquakes', mentioned in the preceding sentence. We have now clarified this accordingly by rephrasing (line 40).

L84-91: About the frictional-viscous mechanism. I would avoid to generalize too much such mechanism as active at crustal scale everywhere as it reads now in the text. It is true that from the outcrop observation of ancient subduction zones and some phyllosilicate-rich faults (e.g. Fagereng et al., 2014; Collettini et al., 2011 these references may be added to the text) this behavior can be inferred as at play. However, this is not true for all the fault zones and I think that it is not appropriate to generalize it. Alternatively, it should be specified that the seismogenic zone refer only to subduction zones here.

We acknowledge that the wording in the original ms was somewhat overconfident here. Part of the 'problem' is the use of the term 'frictional-viscous' which, through time, has received the connotation referred to by the reviewer, as being associated with subduction megathrusts or phyllosilicate-rich faults. However, our intention is much broader than this. In particular, recent observations demonstrate that concurrent brittle/frictional-plastic deformation is widespread in nanogranular fault rocks.

To address the reviewers' point, we now write (lines 85-93)

"Within the seismogenic zone and shallower, field and laboratory observations on a wide range of fault rock types point to the concurrent operation of brittle/frictional (cataclastic) processes that depend linearly on effective normal stress, and rate-sensitive, plastic deformation processes (e.g., pressure solution, dislocation- or diffusion-mediated creep) (Wintsch et al., 1995; Holdsworth et al., 2001; Imber et al., 2008; Collettini et al., 2011; Siman-Tov et al., 2013; Fagereng et al., 2014; Delle-Piane et al., 2018; Verberne et al., 2019). The relation between this 'frictional-plastic' deformation of fault rock and seismogenesis, including of the competing effects between time-sensitive /-insensitive deformation processes on failure, creep, compaction, and healing....."

We thank the reviewer for the references that he/she mentioned, which we have now included. To strengthen our cause, we also mention here the work by Siman-Tov et al., (2013), Delle-Piane et al. (2018), and the review by Verberne et al. (2019), whom demonstrated the importance of frictional-plastic processes in nanogranular fault rock.

L110: since this is a review article I would give credit to the people that put the basis for the friction contact theory such as the work of Bowden and Tabor as well as Rabinowicz and not only Dieterich and Kilgore 1994.

The reviewer is right. We followed his/her suggestion by adding references to Bowden and Tabor (1950, 1964) and Rabinowicz (1956, 1958) (line 111-112).

L330: in regard to the scaling of the critical slip distance with fault thickness I think that the citation to Marone and Kilgore, 1993 Nature is needed.

This is an important result and we thank the reviewer for pointing this out. The relation between d_c and shear band thickness, which the CNS model independently arrives at, is effectively the same as what Marone and Kilgore (1993) arrived at on the basis of RSF analysis. We now mention this in line 334.

References NOT cited in the revised ms

- Scruggs, V. J., & Tullis, T. E. (1998). Correlation between velocity dependence of friction and strain localization in large displacement experiments on feldspar, muscovite and biotite gouge. *Tectonophysics* **295**, 15-40.
- Sleep, N. H., Richardson, E., and Marone, C. (2000). Physics of friction and strain rate localization in synthetic fault gouge. *J. Geophys. Res.* **105**, B11, 25875-25890.

REPLY TO COMMENTS BY REVIEWER #2 SE-2020-85

Below we pasted the reviewers' comments, with in red our reply to each comment made. Where applicable we indicate how/ where a comment has been addressed by referring to line and figure numbers in the revised manuscript (ms).

Anonymous Referee #2

Received and published: 12 August 2020

General comments: This paper summarizes experimental, microstructural, microphysical, and numerical modeling studies of the frictional behavior of simulated gouge conducted at Utrecht University (UU) in the past two or so decades. Although the paper does not have any new results, except some of the modeling results only presented in the recent international conference, it includes the basic information on the experimental setup and results, microphysical model, and numerical modeling of earthquake cycles using their friction model (CNS model). The paper is based on many previous papers presented by UU group and hence it is very well written. Therefore, I recommend publication only after the following minor comments shown below.

We thank the reviewer for his thoughtful comments, which have helped to improve the quality of the ms.

Quality of figures: As mentioned in the reviewer 1, overall quality of figures is too low. Some of the words can't be read. Hence it should be improved.

Yes, point taken. We now apply a consistent style between the figures, and ensured a high resolution (300 DPI) upon exporting the figures to JPEG format. We are confident that this will constitute the high figure quality needed for publication. See also our response to the first comment by Reviewer 1.

The difference in the frictional properties.

Line 258-inset of Fig. 5b: I assume that the authors try to mention the similarity of temperature dependences between calcite (Fig. 5) and qtz-phylllosilicate mixture (Fig. 4a) gouges. However, their variations as a function of temperature are different. In particular, calcite gouges show a wide region of negative v dependence with sharp peaks at 500 C. Can you elaborate more on the difference? Because as shown in later, the CNS model offers fault friction law based on microphysics supported by those experiments. If the authors can illuminate the difference in terms of rock and mineral physics aspects, this will give a more generalized view on the microphysics of fault friction. I assume that is a point the CNS model aims.

This is a good point raised by the reviewer. Taking the CNS model in mind, the shape of the temperature sensitivity of v -dependence (i.e., plotted in Fig. 4a and Fig. 5b) is expected to be dominantly controlled by the rate of intergranular creep. In the case of calcite, intergranular creep occurs by water-assisted diffusive mass transfer at low temperatures ($T < 150^\circ\text{C}$) (Verberne et al., 2014a,b; Chen et al., 2015a,b; Chen & Spiers, 2016), and by dislocation- / diffusion-mediated plasticity at higher temperatures (Verberne et al., 2015; Chen et al., in review). In the case of qtz-phylllosilicate gouges, the intergranular creep mechanisms are more difficult to constrain, and the modelling is more complex (Den Hartog and Spiers, 2014; Niemeijer, 2018). As pointed out in section 7, one of the key remaining challenges is to quantitatively underpin the relevant creep processes in polymineralic gouges, and their incorporation into the CNS model. This remains subject of future study.

Instead of comparing Fig. 4a with Fig. 5b, as mentioned by the reviewer, in fact we wanted to highlight the similarity in the shape of the (a-b) vs T curve with the derivative of

the curves in Fig. 4b (sketched in the inset to Fig. 5b), that is, the inherent prediction from the Den Hartog and Spiers' (2013) model. We realize that this may have been confusing. To address this we now more specifically mention the comparison between Fig. 4b and Fig. 5b-inset (lines 263-266).

Robustness of the CNS mode.

As repeatedly mentioned in the paper, CNS model is based on microphysics supported by experimental results. In that sense, the CNS model provides a transparent origin of the constitutive parameters. However, as shown in Fig. 9 and Chapter 7 (Remaining challenges), the CNS model has a significant shortcoming on that it can only reproduce slow slip or earthquakes with limited coseismic displacement. Hence, I guess that the authors should avoid bold statements on the robustness of the model (e.g., lines 25, 361, 468, and so on).

OK, point taken. When the reviewer mentions that 'the CNS model can only reproduce slow slip or earthquakes with limited coseismic displacement', we assume that he/she is referring to the incorporation of dynamic weakening processes at co-seismic slip rates, or lack thereof. This is indeed the case in its present form (see Section 5), however, the first steps to a unified model are already under way (poster by Chen et al. at GeoProc international conference, 2019).

To address the reviewers' comment, we have rephrased statements on the robustness of the CNS model. We included notes that refer to the challenges ahead (see lines 25-26, 371-374, 468-469).

Lines 169-170: "The maximum rotation or shear displacement that can be achieved is limited by the water cooling and pore fluid systems, ". What does that mean? It is better to elaborate more on the experimental detail for readers outside of the field.

The water cooling and pore fluid systems include connections (i.e., hoses and tubing) to external reservoirs. These connections must be able to accommodate rotation of the vessel. Smart designs have helped to accommodate rotation such that very large sample displacements can be achieved (>100 mm). Following the reviewers' suggestion, we rephrased line 176-177 in accordance with the above.

Line 240 and Fig. 4: Need a more detailed explanation of the Fig. 4 (in particular 4c). For example, explanations on the differences in color and meaning of peaks in dash-lines are needed.

OK. We have improved the overall quality of Figure 4 (see reply to first comment), including readability of Fig. 4c. We rewrote the caption to ensure that all abbreviations, symbols, colours, etc used are explained (applies to all figures), and we included a description on the meaning of the peaks in Fig. 4c.

Line 250: "an important role for the presence of (pressurized) pore water (Fig. 5a- insets) But how can we understand the importance of ((pressurized) pore water) from Fig. 5a?"

The data shown in Fig. 5a are from experiments on simulated calcite gouge carried out under the same effective normal stress and temperature conditions, one lab-dry and the other using a pore fluid pressure of demineralized water of 10 MPa. The inset highlights a part of the slide-hold-slide sequence in the test, demonstrating a marked difference in healing behaviour (i.e., note $\Delta\mu_r$).

We acknowledge that this was not sufficiently clear in the original ms, and we thank the reviewer for pointing this out. To address this, we now refer to Fig. 5a-inset at the appropriate location in the text, including a note on $\Delta\mu_r$ (see line 260-261). Furthermore, we have

clarified the text within, and caption to, Figure 4, to better indicate the dry vs. wet experiment.

References NOT cited in the revised ms:

Chen, J., Verberne, B. A., and Niemeijer, A. R. Flow-to-friction transition in simulated calcite gouge: Experiments and microphysical modelling. *Under review for publication in J. Geophys. Res.*, preprint available on ESSOAr, 25 April, <https://doi.org/10.1002/essoar.10502888.1>.

The physics of fault friction: Insights from experiments on simulated gouges at low shearing velocities

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Abstract. The strength properties of fault rocks at shearing rates spanning the transition from crystal-plastic flow to frictional slip play a central role in determining the distribution of crustal stress, strain, and seismicity in tectonically-active regions. We review experimental and microphysical modelling work aimed at elucidating the processes that control the transition from pervasive ductile flow of fault rock to rate-and-state-dependent frictional (RSF) slip and to runaway rupture, carried out at Utrecht University in the past two or so decades. We address shear experiments on simulated gouges composed of calcite, halite-phylosilicate mixtures, and phyllosilicate-quartz mixtures, performed under laboratory conditions spanning the brittle-ductile transition. With increasing shear rate (or decreasing temperature), the results consistently show transitions from 1) stable, velocity(v)-strengthening to potentially unstable, v -weakening behavior, and 2) back to v -strengthening. Sample microstructures show that the first transition, seen at low shear rates and/or high temperatures, represents a switch from pervasive, fully ductile deformation to frictional sliding, involving dilatant granular flow in localized shear bands, where intergranular slip is incompletely accommodated by creep of individual mineral grains. A recent microphysical model, treating which treats fault rock deformation as controlled by a competition between rate-sensitive (diffusional or crystal-plastic) deformation of individual grains and rate-insensitive sliding interactions between grains (granular flow), predicts both transitions well. Unlike classical RSF approaches, this model quantitatively reproduces a wide range of (transient) frictional behaviors using input parameters with direct physical meaning, with the latest progress focusing on incorporation of dynamic weakening processes characterizing co-seismic fault rupture. When implemented in numerical codes for crustal fault-slip, the model offers a single, unified framework for understanding slip patch nucleation and growth to critical (seismogenic) dimensions, and for simulating the entire seismic cycle.

1 Introduction

Earthquakes are the result of a sudden release of energy during rapid slip (> 1 m/s) along geologic fault zones in the Earth’s crust or upper mantle, which generates seismic waves that can be highly destructive at Earth’s surface. Throughout history,

earthquakes and associated tsunamis have claimed countless lives and caused severe material and economic damage (Guha-Sapir et al., 2016), with their impact increasing today as urban populations in tectonically active regions continue to increase. It is therefore of utmost importance to improve prognoses on the frequency, location, and magnitude of future seismic events.

35 This demands sophisticated modelling of earthquake nucleation and dynamic rupture propagation, which in turn requires a fundamental understanding of fault sliding, or more specifically the internal fault rock shearing mechanisms, that are active under in-situ conditions in the Earth.

Tectonically-loaded faults can exhibit aseismic slip transients (“creep”) without producing earthquakes, or else sporadic unstable slip, resulting in slow-slip events or catastrophic failure as the case for earthquakes (Scholz et al., 1969; Peng and
40 Gombert, 2010). ~~Seismic~~Unstable or seismic fault motion ~~of this type~~ can occur at the lithosphere-scale such as along subduction zone megathrusts (Simons et al., 2011; Nishikawa et al., 2019), at the reservoir scale as in the case of human-induced seismicity (Elsworth et al., 2016; Grigoli et al., 2018), but also within mm- to m-scale samples in the laboratory (Passelègue et al., 2013; Yamashita et al., 2015; Ikari, 2019). The fault zones involved typically show a multi-scale, self-affine structure characterized by shear strain localization into narrow, principal slip zones (PSZs) (Tchalenko, 1970; King, 1983;
45 Sibson, 2003), suggesting that the rheology of the comminuted fault rock or “gouge” within PSZs controls macroscopic fault behaviour. From a mechanistic point of view, improvement of seismic hazard assessments and forecasting requires rationalization of the physics of the earthquake source, as controlled by the material properties of, and deformation processes active within, sheared fault rock.

Laboratory investigations of fault-slip performed under conditions relevant to Earth’s upper-crust are key to probing the
50 physics of fault behaviour and seismogenesis. The mechanical data serves as direct input for empirically-based numerical simulations of fault rupture (e.g., Tse and Rice, 1986; Noda and Lapusta, 2013), while post-mortem observations of recovered deformed specimens can be used to infer the underlying physical processes controlling deformation (e.g., Gu and Wong, 1994; Heilbronner and Keulen, 2006; Peč et al., 2016). In general, we can distinguish two types of laboratory fault-slip experiments. Firstly, low-velocity friction (LVF) tests are used to investigate both stable fault creep and the early (nucleation) stages of
55 earthquake rupture. These LVF experiments are typically conducted at imposed shearing velocities (v) of nm to μ m or mm per second, under fixed conditions of normal stress (σ_n) and temperature (T). Secondly, high-velocity friction (HVF) tests are used to investigate dynamic earthquake slip processes that occur during unstable, runaway slip at slip velocities of 1 to 10 m/s (see Heaton, 1990). In HVF tests, frictional heating at the slipping fault interface triggers thermally-activated processes such as pore fluid-pressurization, phase changes and melting, which come to dominate the evolution of fault strength (Rice, 2006; Di
60 Toro et al., 2011; Yao et al., 2016); ~~Rattez and Veveakis, 2020~~). In recent years, technological improvements in both LVF and HVF apparatus, as well as of electron beam and other instruments used to perform post-mortem micro- and nanostructural analyses, have enabled major advances in the understanding of fault rock material properties and crustal fault rheology (for reviews see De Winter et al., 2009; Viti, 2011; Niemeijer et al., 2012; Rowe and Griffith, 2015; Chen et al., 2015a).

In this paper we integrate findings from experimental, microstructural, microphysical, and numerical modelling studies of the
65 frictional behaviour of gouge-filled faults in the low velocity or nucleation regime, conducted at Utrecht University (UU) in

the past two or so decades. Our aim is to provide a unified view of the physics of fault friction behaviour at low velocities. We begin with a summary of key concepts and definitions, followed by a summary of the LVF experimental techniques used at UU. We go on to present key results from experiments on simulated faults composed of halite-phyllisilicate and phyllisilicate-quartz mixtures, and of calcite. Data from these experiments consistently suggest that low velocity frictional deformation of fault gouge is controlled by a competition between rate-sensitive (diffusional or crystal-plastic) deformation and rate-insensitive sliding interactions (dilatant granular flow) — a competition which was already suggested on the basis of theoretical considerations by Rutter and Mainprice (1979). This forms the foundation for a unified microphysical modelling approach for low velocity sliding and static healing of gouge-filled faults, described in progressive detail by Niemeijer and Spiers (2007) and by Chen and Spiers (2016), for example, and referred to here for convenience as the “Chen-Niemeijer-Spiers” (CNS) model. We outline the principles of this model, and present some applications and implications in reproducing laboratory data and in numerical simulations of earthquake nucleation and the full earthquake cycle.

2 Crustal fault strength and fault-slip models

The strength of Earth’s crust is classically approximated using a Coulomb-type, brittle/frictional failure law representing the upper part, which abruptly gives way to ductile deformation (here used synonymously with “plastic” deformation to indicate non-dilatant permanent deformation) below ~10 to 20 km depth depending on the geothermal gradient (Fig. 1) (Byerlee 1978; Brace and Kohlstedt, 1980; Kohlstedt et al., 1995). A brittle-to-ductile transition within this depth range is consistent with geological and seismological observations of a depth interval in the crust where the majority of earthquakes nucleate, known as the “seismogenic zone” (Sibson, 1982, 1983; Meissner and Strehlau, 1982; Scholz, 1988, 2019). In the fully ductile regime, stress buildup and associated rupture nucleation is inhibited by ~~viseous~~plastic flow in shear zones, which is achieved by solid state diffusive mass transfer and/or dislocation-mediated deformation mechanisms active at the grain-scale (e.g., Karato, 2008).

~~Within the seismogenic zone and shallower it is now widely accepted that faults display so-called ‘frictional-viseous’ deformation at steady tectonic slip rates (Fig. 1), characterized by, field and laboratory observations on a wide range of fault rock types point to the concurrent operation of brittle/frictional (cataclastic) processes, that depend linearly on effective normal stress, plus viseous and rate-sensitive, plastic deformation processes (typically (e.g., pressure solution, dislocation- or diffusion-mediated creep) (Wintsch et al., 1995; Holdsworth et al., 2001; Imber et al., 2008; Takeshita and El-Fakharani, Collettini et al., 2011; Siman-Tov et al., 2013); Fagereng et al., 2014; Delle-Piane et al., 2018; Verberne et al., 2019). The relation between this ‘frictional-viseousplastic’ deformation in of fault zones rock and seismogenesis, including of the competing effects of eataclasis and pressure solution between time-sensitive /-insensitive deformation processes on failure, creep, compaction, and healing – and how these control the depth range of the seismogenic zone – remain subjects of intensive study in fault mechanics and fault geology (e.g., Gratier et al., 2013; He et al., 2013; Fagereng and Den Hartog, 2016; Gao and Wang, 2017; Reber & Peč, 2018; Aharonov and Scholz, 2018, 2019; Collettini et al., 2019; Rattez et al., 2019; Masuda et al., 2019; Hirauchi et al., 2020).~~

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In a strictly phenomenological sense, earthquakes are analogous to the recurring frictional instability that is frequently observed in laboratory rock friction experiments known as “stick-slip” (Brace and Byerlee, 1966). Byerlee (1970) proposed that a frictional instability may arise from sudden weakening of the fault interface combined with a sufficiently low shear stiffness of the surrounding medium (experimental apparatus or host rock). However, this ‘slip-weakening’ model does not include a mechanism for the intrinsic fault re-strengthening or ‘healing’ ~~mechanism~~ which is required to account for long-term, repetitive slip events (Dieterich, 1979a). To capture the time- and sliding velocity-dependent effects of fault friction, in an empirical way, Dieterich (1979a, b) proposed a rate and “age” dependent friction model that was later recast by Ruina (1983) in terms of the rate-and-state-dependent friction equations (RSF), given by

$$\mu = \mu_{ss}^* + a \ln\left(\frac{v}{v^*}\right) + b \ln\left(\frac{v\theta}{d_c}\right) \quad (1)$$

$$\dot{\theta} = 1 - \frac{v\theta}{d_c} \quad (2a)$$

$$\dot{\theta} = -\frac{v\theta}{d_c} \ln\left(\frac{v\theta}{d_c}\right) \quad (2b)$$

where μ is the coefficient of friction, defined as shear stress over effective normal stress (ignoring cohesion), μ_{ss}^* is the steady-state coefficient of friction at a reference sliding velocity v^* , v is the instantaneous slip velocity, a is a parameter that quantifies the “direct effect”, b is the parameter that describes the “evolution effect”, and d_c is a characteristic or critical slip distance over which the state variable, θ , evolves (for reviews see Marone, 1998; Scholz, 1998, 2019). The state variable θ has units of time and is thought to represent the average lifetime of grain-scale asperity contacts (at steady-state; Scholz, 2019). The conceptual interpretation of RSF finds its origin in two observations, namely that the true area of contact of any interface is always smaller than the nominal contact area, and that this area of contact changes with time (Bowden and Tabor, 1950, 1964; Rabinowicz, 1956, 1958; Dieterich and Kilgore, 1994). The equations for the state variable time derivative ($\dot{\theta}$; eqs. 2a and 2b) embody two views of how a population of contacts may evolve during slip. Equation 2a is sometimes called the “slowness” or “aging” (Dieterich) law, because in this formulation, the frictional contact area continues to evolve in the absence of slip, whereas in equation 2b, slip is needed for the state variable to evolve. Accordingly, the latter equation is called the “slip” (Ruina) law.

In the case of steady state sliding ($\mu = \mu_{ss}$; $\dot{\theta} = 0$) both the slowness and slip laws reduce to

$$\mu_{ss} = \mu_{ss}^* + (a - b) \ln\left(\frac{v}{v^*}\right) \quad (3)$$

where $(a-b)$ represents a dimensionless quantity that characterizes the velocity(v)-dependence of the sliding surface. Ruina (1983) showed that for an instability to nucleate spontaneously and repeatedly (i.e., the case of stick-slip), the sliding surface must decrease in strength with increasing velocity, hence be v -weakening, characterized by $(a-b) < 0$. In the opposite case v -strengthening occurs, characterized by $(a-b) > 0$, which leads to a state of stable sliding (Ruina, 1983; Rice and Ruina, 1983).

Linear stability analysis of a single-degree-of-freedom spring-slider model demonstrated a critical stiffness K_c below which sliding is unstable (Ruina, 1983)

$$K_c = \frac{(b-a) \cdot \sigma_n^{eff}}{d_c} \quad (4)$$

Thus, an instability may occur when the stiffness of the deforming medium falls below K_c , and $(a-b) < 0$. Importantly, when applied to natural ~~fault deformation~~ faults, the $(a-b)$ -value or ν -dependence of the sliding medium is a material property of deforming ~~fault~~ rock in the fault core, ~~which is and its constitutive properties are~~ strongly affected by coupled thermo-hydro-mechanical-chemical processes in the general sense. With reference to Earth's crust and Figure 1, the seismogenic zone is believed to represent the depth interval where shear deformation of fault rock leads to ν -weakening behavior, as opposed to ν -strengthening above and below.

The RSF approach has enabled a simple and highly successful description of laboratory rock friction behavior over a wide range of conditions (~~for reviews see~~ Marone, 1998; Scholz, 1998, 2019), and is widely used in numerical simulations of the earthquake cycle (e.g., Dieterich, 1994; Lapusta and Rice, 2003; Ampuero and Rubin, 2008; Matsuzawa et al., 2010; Noda and Lapusta, 2013; Ohtani et al., 2014). However, laboratory observations and microphysical modelling show that the empirically fitted parameters appearing in the RSF equations, notably the values of $(a-b)$ and d_c , are not fundamental, independently measurable material constants (Ikari et al., 2016; Aharonov and Scholz, 2018). The implication is that extrapolation to natural conditions not attainable in the laboratory presents a significant source of uncertainty in numerical modelling (for a discussion see Ide, 2014; Van den Ende et al., 2018). To address this, a (micro)physically based interpretation and description of the processes controlling fault deformation is needed. ~~Based on data from friction experiments on simulated quartz gouges at room temperature, Marone et al. (1990) hypothesized that dilatation and shear strain localization play a key role in controlling gouge shear strength and velocity dependence. Despite the key importance and application of their experimental findings and conceptual explanation (see e.g., Segall and Rice, 1995; Beeler et al., 1996), friction models derived from this pioneering work and fitted to experimental data lack a rigorous microphysical basis.~~ An example of a mechanistically-based, and microstructurally founded model developed to explain ν -dependence effects of fault rock friction, proposed by Bos, Niemeijer, and Spiers (Bos and 2002a; Niemeijer and Spiers, 2006, 2007), is based on the accommodation of shear deformation by a combination of frictional and ~~viscous~~ plastic deformation processes. It was demonstrated that if the rates of intergranular compaction ($\dot{\epsilon}_{cp}$) and dilatation ($\dot{\epsilon}_{dil}$) are of comparable magnitude, or $|\dot{\epsilon}_{dil}| \approx |\dot{\epsilon}_{cp}|$, this leads to ν -weakening behavior, whereas under conditions where either process dominates, stable ν -strengthening occurs. ~~Viewed~~ In other words, in this framework, the seismogenic zone corresponds to a depth interval where shear deformation of gouge-filled faults is characterized by $|\dot{\epsilon}_{dil}| \approx |\dot{\epsilon}_{cp}|$ (Fig. 1).

3 Low-velocity friction (LVF) testing methods

Research on low-velocity rock friction at UU ~~involved~~includes fault-slip experiments ~~carried-out~~ under pressure-~~temperatures~~ temperature conditions that range from ambient surface conditions to those relevant throughout the upper ~20-30 km of the Earth's crust. ~~Because of their critical role in~~To achieve this research, ~~below we summarize~~ the ring- and direct-shear testing methods ~~installed~~developed at UU, ~~and summarized below, play a critical role.~~ For more details on ~~experimental~~the testing procedures and data analysis methods employed we refer to the various papers cited ~~below~~.

Ring shear LVF experiments at UU are conducted using two distinct set-ups that are interchangeable within a single, rotary-shear deformation apparatus, ~~which consists~~consisting of an Instron loading frame with electrically-~~actuated~~ ram for axial loading (application of normal stress) plus a rotation drive for imposing shear displacement onto the sample (Figs. 2a, b). The earliest ring-shear assembly ~~was~~, developed in the late 1990's (Bos et al., 2000a), ~~and enabled~~enables simulated fault sliding tests at room temperature and at elevated normal stresses and pore fluid pressures (up to ~10 MPa), achieving in principle unlimited rotational displacements. The simulated fault sliding rates that can be achieved depend on the arrangement of gear boxes used, and ranges from 3 nm/s to up to 1 cm/s. The assembly consists of two grooved piston rings (inner diameter 80 mm, outer diameter 100 mm) that grip a ~1-2 mm thick, annular sample layer upon the application of normal stress, with radial confinement facilitated by tightly-fitting inner and outer rings (Figs. 2a, d). This room temperature ring-shear set-up has played an important role in investigations of shear deformation of monomineralic halite and halite-phylllosilicate mixtures (e.g., Takahashi et al., 2017; Van den Ende and Niemeijer, 2019), and of granular system dynamics using synthetic polymer and glass beads (Kumar et al., 2020).

A later, 'hydrothermal', ring-shear assembly was designed and commissioned in 2002-2005 (Fig. 2b, e), with the aim of enabling high shear strain, rotary-shear tests under pressures, temperatures, and displacement rates representative for the seismogenic reaches of crustal scale faults and subduction megathrusts (Niemeijer et al., 2008; Van Diggelen et al., 2010; Den Hartog et al., 2012a, b). In this setup, the piston-sample assembly is located in a pressure vessel with internal furnace, which in turn is emplaced within the Instron frame with rotation drive (Fig. 2b). A ~1 mm thick sample layer is sandwiched between a set of grooved pistons, and prevented from extruding by an inner confining ring with a diameter of 22 mm, and an outer confining ring with a diameter of 28 mm (Fig. 2e). The vessel is pressurized with water, which has direct access to the sample thus providing the pore fluid pressure. Experiments in this setup can be conducted at effective normal (axial) stresses up to 300 MPa (provided by the Instron frame), temperatures up to 700°C, and pore fluid pressures up to 300 MPa. The rotary drive system provides simulated fault zone displacement rates ranging from around 1 nm/s to several mm/s. The maximum rotation or shear displacement that can be achieved is limited by the connections of the water cooling and pore fluid systems to their respective external reservoirs, but is in practice very large (>100 mm). The hydrothermal ring shear machine has been used extensively in investigations of the shear behavior of rock compositions believed to be widespread along subduction megathrust faults (e.g., Hirauchi et al., 2013; Ikari et al., 2013; Sawai et al., 2016, 2017; Kurzwski et al., 2016, 2018; Boulton

et al., 2019; Okamoto et al., 2019, 2020) and in the upper and middle continental crust (Niemeijer and Collettini, 2014; Niemeijer and Vissers, 2014; Niemeijer et al., 2016; Hellebrekers et al., 2019).

190 Direct-shear tests are carried out using a ‘conventional’, externally or internally heated, oil-medium, triaxial deformation apparatus, such as that shown in Figure 2c. Following the design of Logan et al. (1992), the direct-shear or “69” assembly comprises two L-shaped pistons in a jacketed face-to-face (l^1) arrangement that sandwiches a cuboid sample (Figs. 2f). A soft, near-Newtonian viscous material (such as silicone putty) or soft elastomer fills the voids at the top and bottom of the assembly (Samuelson and Spiers, 2012; Sánchez-Roa et al., 2016). In the set-up used at UU, the sample measures 35 mm wide
195 by 49 mm long with a thickness of typically ~1 mm. Direct-shear experiments can be carried out at confining pressures (= normal stress) and pore pressures up to 100 MPa, temperatures up to 150°C, reaching shear displacements up to ~6 mm. The direct-shear assembly has proven especially useful for tests employing corrosive pore fluid compositions such as reservoir brine or CO₂ (e.g., Pluymakers et al., 2014; Pluymakers and Niemeijer, 2015; Bakker et al., 2016; Hunfeld et al., 2017, 2019).

4 Low velocity friction experiments on simulated gouges – some case studies

200 4.1 Halite-phyllsilicate mixtures

Bos et al. (2000a, b) and Bos and Spiers (2000, 2001, 2002a, b) employed the room temperature ring-shear assembly (Fig. 2a, d) to investigate the shear behaviour of brine-saturated, simulated fault gouge composed of (mixtures of) halite and kaolinite. Bos and co-workers’ experiments were carried out under conditions favouring rapid pressure solution in the halite-brine system, which is well-constrained from compaction tests and microphysical modelling (Spiers et al., 1990; Spiers and
205 Schutjens, 1990). Kaolinite was added in varying proportions to investigate the effect on shear behaviour, while simulating the presence of phyllosilicates that are observed to be widespread in natural fault zones (e.g., Wintsch et al., 1995; Holdsworth, 2004; Takeshita and El-Fakharani, 2013). The aim was to elucidate the combined role of pressure solution creep and foliation development in controlling the strength of faults in the upper-crust, viewing the halite-kaolinite mixtures ~~used~~ as a mid-crustal rock analogue (cf. see e.g., Shimamoto, 1986; Hiraga and Shimamoto, 1987; Chester and Logan, 1990). Velocity (v -) and
210 normal stress (σ_n -) stepping experiments (Fig. 3a), as well as post-mortem microstructural analyses which revealed a classical, foliated mylonitic (i.e., phyllonitic) microstructure (Fig. 3b), pointed to frictional-viscous flow in the case of halite-kaolinite mixtures, but to purely frictional behaviour in the case of the monomineralic end-member gouges (Fig. 3a). Based on these results, Bos and Spiers (2001, 2002a) proposed a micromechanical model for the combined effect of frictional sliding on phyllosilicate folia, pressure solution of halite clasts, and dilatation on the foliation (Fig. 3c), ~~which~~. This model offered the
215 first microstructurally-based interpretation for v -strengthening, frictional-viscous flow of gouge-filled faults.

Niemeijer and Spiers (2005) refined the Bos and Spiers’ model by incorporating effects of plasticity of phyllosilicate folia and a distributed grain size. Moreover, their experiments used muscovite instead of kaolinite and covered a wider range of sliding velocities. ~~This allowed them to identify~~ Their experiments revealed a v -weakening regime beyond $v = 1 \mu\text{m/s}$ (Fig. 3d), characterized by a strong increase in porosity with increasing v (Niemeijer and Spiers, 2005, 2006). Compared with v -

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strengthening samples, those deformed under v -weakening conditions showed a chaotic, cataclastic microstructure (Fig. 3e). On this basis it was hypothesized that v -weakening results from a competition between dilatation by granular flow and intergranular compaction by pressure solution (Niemeijer and Spiers, 2006). This microphysical model concept was further developed and quantified to enable calculation of steady-state shear strength in the v -weakening regime based on physically meaningful input parameters such as the kinetics parameters for pressure solution, porosity, and dilation angle for granular flow (Niemeijer and Spiers, 2007) (Fig. 3f). By combining the model for frictional-viscous flow with that for v -weakening frictional sliding, the lab-observed transition from v -strengthening to v -weakening with increasing shear displacement rate in halite-phyllsilicate mixtures could be accurately reproduced.

4.2 Phyllosilicate-quartz mixtures

The experiments using halite-phyllsilicate mixtures as a fault rock analogue system trigger the inevitable question of whether the same processes and mechanical behaviour really occur within crustal faults. Specifically, the microphysical models developed for v -dependence of gouge-filled faults required testing for real crustal fault rock types, under conditions relevant for the seismogenic zone. With this in mind, Den Hartog et al. (2012a, b, 2013, 2014) investigated the frictional behaviour of phyllosilicate-quartz gouge mixtures using the hydrothermal ring shear apparatus (Fig. 2b, d), under P-T conditions broadly representative for the seismogenic reaches of a subduction zone megathrust. The samples consisted mainly of 65:35 illite:quartz gouge mixtures, but muscovite-quartz gouge mixtures and clay-rich samples derived from the Nankai Oceanic Drilling Project (Leg 190) were also tested. Experiments were carried out at effective normal stresses (σ_n^{eff}) ranging from 25 to 200 MPa, at pore fluid pressures (P_f) of 0 (dry) to 200 MPa, and temperatures (T) of 100°C to 600°C. The data consistently showed v -strengthening behaviour at relatively low temperatures (up to ~250-350 °C, Regime 1), v -weakening at intermediate temperatures (~250-500 °C, Regime 2), and again v -strengthening at the highest temperatures investigated (>500 °C, Regime 3) (Fig. 4a). Such ‘three-regime’ v -dependence with increasing temperature has been observed for granite (Blanpied et al., 1991, 1995) and gabbro (He et al., 2007) gouges, but Den Hartog and co-workers were the first to report this for a realistic megathrust fault rock composition. ~~Moreover, the~~ The temperature range in which v -weakening was reported is broadly consistent with the temperature-depth range of the subduction seismogenic zone such as in Nankai (Hyndman et al., 1997; Yoshioka et al., 2013; Okamoto et al., 2019).

The above observations on illite- and muscovite-quartz gouges were explained first qualitatively and later using a quantitative model based on the Niemeijer and Spiers (2007) approach, but employing a phyllosilicate-dominated model microstructure (Fig. 4b) (Den Hartog and Spiers, 2013, 2014; see also Noda, 2016). The change in the sign of $(a-b)$ with increasing temperature was proposed to occur due to changes in the ~~relative importance~~ role of thermally-activated deformation of the quartz clast phase (by stress corrosion cracking and/or pressure solution) versus ~~that of~~ athermal granular flow of the mixture accompanied by dilatation (Fig. 4b). ~~Moreover, on~~ On the basis of widespread experimental observations (Ikari et al., 2011), expected v -strengthening effects of frictional slip within the phyllosilicate matrix and foliation were taken into account. ~~Using~~ Assuming pressure solution as the controlling thermally-activated process, the experimentally observed ‘three-regime’

v-dependence could be reproduced. ~~In addition~~On the other hand, Niemeijer (2018) recently showed a good match between data from constant- v shear experiments using 80:20 quartz:muscovite gouges, and predictions of the “Bos-Spiers-Niemeijer” model for frictional-viscous flow model (Bos and Spiers, 2002a; Niemeijer and Spiers, 2005) (Fig. 4c). Regardless of the details of the model used, the results of Den Hartog and co-workers, and those of Niemeijer (2018), imply that shear strain accommodation involving a competition between rate-sensitive (thermally-activated creep of clast phases) and rate-insensitive processes (dilatant intergranular sliding), plays a key role in controlling v -dependent frictional and frictional-viscous flow of phyllosilicate-quartz mixtures.

4.3 Calcite

Motivated by the frequency of destructive earthquakes in tectonically-active carbonate-bearing terranes such as the Apennines (Italy) and the Longmen Shan (China), Verberne et al. (2013, 2014a, b, 2015) and Chen et al. (2015b, c, 2020a) investigated the frictional behaviour of simulated calcite(-rich) fault gouge. Initial experiments employing the direct-shear assembly (Fig. 2c, f) were conducted at $T = 20$ -150 °C, $\sigma_n^{eff} = 50$ MPa, and a pore water pressure $P_f = 10$ MPa or else under room-dry conditions. Dry and wet velocity-stepping ($v = 0.1, 1, 10$ $\mu\text{m/s}$) experiments consistently showed a thermally-activated transition from v -strengthening to v -weakening at 80-100°C (Fig. 5a, b, ~~while~~). Furthermore, results from fault healing (‘slide-hold-slide’ or SHS) tests pointed to an important role for the presence of (pressurized) pore water (Fig. 5a-insets). Specifically, ~~dry~~ Dry samples exhibited classical ‘Dieterich-type’ healing behaviour (Dieterich, 1978), characterized by a transient peak in shear resistance after each hold period with no effects on steady-state frictional strength (Chen et al. 2015b, e). By contrast, wet experiments showed i) an increase in apparent steady-state friction upon re-sliding after a hold period; (note $\Delta\mu_s$ in Fig. 5a-inset), and ii) a pronounced increase of $(a-b)$ after the SHS stage. Using the hydrothermal ring shear machine (Chen et al., 2015b, c), Verberne et al. (2015) extended the temperature range to 600°C, which demonstrated of shear tests on simulated calcite gouge to 600 °C, using the hydrothermal ring shear apparatus, and employing a constant effective normal stress of 50 MPa. The results showed a three-regime trend in $(a-b)$ -values with increasing temperature, reminiscent of that discussed above for phyllosilicate-quartz gouges (predicted by Den Hartog and Spiers, 2013; see inset Fig. 5b). Chen et al. (2020a) demonstrated a striking consistency between experimental data spanning the frictional-to-viscous transition in simulated calcite gouge and a microphysical Spiers’ model that is based on (i.e., the derivative of the foundations laid by Bos, Niemeijer, and Spiers (described curves in detail below) Fig. 4b, sketched in the inset to Fig. 5b) (Den Hartog & Spiers, 2013, 2014; Verberne et al., 2015).

Regardless of the large changes in $(a-b)$ observed in LVF experiments on simulated calcite gouge, the microstructures formed at temperatures up to 550 °C consistently showed localization into at least one, narrow (<100 μm), boundary-parallel shear band. At low temperatures (<150 °C), boundary shears represent a porous, sheet-like volume of calcite nanocrystallites (grain size down to 5 nm) that are locally arranged in dense patches composed of ~ 100 nm wide spherical grains and fibres (Fig. 5c-inset) (Verberne et al., 2014a, b, 2019). Towards higher temperatures (400-550 °C) the shear band is composed of linear, cavitated arrays of polygonal grains (~ 0.3 -1 μm in size), suggestive of incomplete grain boundary sliding and (possible post-

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test) grain growth (Fig. 5d) (Verberne et al., 2017; ~~Chen et al., 2020a~~). The nano- and microcrystalline boundary shears developed in experiments carried out at ≤ 550 °C showed a strong crystallographic preferred orientation (Verberne et al., 2013, 2017). Somewhat surprisingly, the post-mortem calcite gouge microstructures resemble those formed in HVF experiments using simulated gouge material of similar compositions (Smith et al., 2013; De Paola et al., 2015; Rempe et al., 2017; Pozzi et al., 2019). Above 550 °C, a more homogeneous (non-localized), plastically deformed and recrystallized microstructure is observed, consistent with flow controlled by dislocation and possibly diffusional deformation mechanisms (Verberne et al., 2015, 2017; ~~Chen et al., 2020a~~).

5 The Chen-Niemeijer-Spiers microphysical model for shear of gouge-filled faults

Inspired by the modelling work by Bos, Niemeijer, Den Hartog, and Spiers (Figs. 3, 4), and the observations on monomineralic calcite gouge (Fig. 5), Chen and Spiers (2016) developed a more general microphysical model for (localized) shear deformation of gouge-filled faults. This model employs rate-strengthening grain boundary friction plus standard equations for pressure solution creep, and covers both steady state and transient gouge shearing behaviour. It is capable of reproducing results from ν -stepping as well as SHS tests, using physically-based, independently measured input parameters. In the following, we describe the main features of this “Chen-Niemeijer-Spiers” (CNS) model.

5.1 Model outline

The CNS model assumes an idealized geometry for fault gouge that consists of a densely packed, 2-dimensional array of cylinders or spheres, while allowing for localized deformation in a boundary-parallel shear band located at the margin of a bulk gouge zone (Fig. 6). The shear band and the bulk ~~sample~~ are represented by the same grain packing geometry, but with different nominal grain diameters internally. Deformation of the gouge layer is controlled by parallel processes active within each zone, ~~specifically that is~~, dilatant granular flow plus a creep ~~mechanism process~~ such as intergranular pressure solution (IPS). The model considers frictional energy dissipation for a constant grain size and shear band thickness, ignoring ~~processes such as~~ (de-)localization, grain rolling, ~~or and~~ comminution (cataclasis, microcracking). The ~~underlying governing~~ constitutive equations are derived from kinematic, energy/entropy considerations (Chen and Spiers, 2016);

$$\tau = \sigma_n^{eff} \frac{\tilde{\mu} + \tan(\psi)}{1 - \tilde{\mu} \tan(\psi)} \quad (5a)$$

$$\tilde{\mu} = \tilde{\mu}^* + a_{\tilde{\mu}} \ln \left(\frac{\dot{\gamma}_{gr}}{\dot{\gamma}_{gr}^*} \right) \quad (5b)$$

$$\frac{\dot{\phi}}{(1-\phi)} = -\dot{\epsilon}_{pl} + \dot{\gamma}_{gr} \tan \psi \quad (5c)$$

where τ is shear stress, σ_n^{eff} ~~is~~ the effective normal stress, and ϕ ~~is the~~ shear band porosity. Further, $\dot{\gamma}$ and $\dot{\epsilon}$ are respectively the shear and normal strain rates, where the subscripts “ pl ” indicates time-dependent ~~duetile-(plastic)~~ creep and “ gr ” ~~indicates~~

granular flow. Equation 5a represents the “friction law” of the CNS model, in which shear resistance is expressed in terms of grain boundary friction $\tilde{\mu}$ and the resistance due to intergranular dilatation, $\tan(\psi)$, where ψ is the mean dilatancy angle of the shearing grain pack (Fig. 6). An intrinsically rate-v-strengthening, cohesionless grain boundary slip criterion is adopted (eq. 5b), where $a_{\tilde{\mu}}$ is a strain rate-dependent coefficient and $\tilde{\mu}^*$ is the grain boundary friction coefficient at a reference shear strain rate $\dot{\gamma}_{gr}^*$. Equation 5c captures the evolution of porosity and deformation in the fault-normal direction (i.e., volumetric strains). Granular flow implies dilatation, or $\dot{\epsilon}_{gr} = -\dot{\gamma}_{gr} \tan(\psi)$ (Paterson, 1995; Gudehus, 2011). By contrast with the classical RSF equations, the evolving “state” variable in the CNS model is porosity (eq. 5c), which is clearly physically measurable and microstructurally quantifiable, as opposed to that characterizing the classical RSF equations (eq’s. 1, 2). To capture transient frictional behaviors, such as occurring upon a perturbation in displacement rate, the deforming gouge plus elastic surrounding (testing apparatus or host rock) is modelled as a spring-slider system assuming zero inertia. Recently, Chen et al. (2019) extended the CNS model to seismic slip rates (~ 1 m/s), incorporating superplastic flow activated by frictional heating (De Paola et al., 2015). This refined model is capable of predicting not only low velocity frictional behavior but also (the transition to) rapid dynamic weakening effects frequently seen in high-velocity friction experiments (see Di Toro et al., 2011).

5.2 Comparison with lab data and model predictions

The CNS model has been strikingly successful in reproducing the mechanical behaviours observed in laboratory fault slip experiments (Figs. 7a, b) (Chen and Spiers, 2016; Chen and Niemeijer, 2017; Chen et al., 2017, 2020a, b, 2019, 2020; Hunfeld et al., 2019, 2020). In order to reproduce experimental data, the parameters appearing in equations 5a-c are either implicit from the testing configuration used, experimentally-derived values, or else values derived from postmortem microstructural analysis. The model shows favorable consistency with laboratory observations, predicting a dependence of the steady-state friction coefficient on sliding velocity, including a transition from v-weakening to -strengthening with increasing v (Fig. 7a). Transient strength data upon imposed steps in sliding velocity are also reproduced well, which demonstrates the capability of the CNS model to reproduce the sign of displacement rate and magnitude of (a-b) values, as well as decaying strength oscillations are also reproduced well (Fig. 7b - see the step from 1 to 0.1 $\mu\text{m/s}$). When applied over a wide range of sliding velocities, the CNS model output for the steady-state friction coefficient essentially represents a flow-to-friction profile (Fig. 7c), characterized by transitions with increasing v from v-strengthening, to -weakening, back to v-strengthening, and finally, v-weakening associated with dynamic, thermal weakening at high velocities (Chen and Niemeijer, 2017; Chen et al., 2019). These v-dependence transitions are accompanied by marked changes in mean porosity (bottom Fig. 7c). In the intermediate velocity weakening regime, the mean porosity increases with increasing v to relatively high values, however, this decreases to much lower levels when creep becomes the dominant deformation mechanism. Since decreasing shear strain rate in the model is, to some extent, equivalent to an increase in temperature (Bos and Spiers, 2002; Tenthorey and Cox, 2006; Den Hartog and Spiers, 2013), the model can also be used to predict v-dependence transitions with increasing temperature.

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Using the CNS model, the above critical 'critical' sliding velocities or temperatures that marking transitions in fault gouge v -dependence can be obtained derived theoretically. Moreover, the CNS model can be used to derive analytical solutions for the RSF parameters a , b , and d_c , as functions of fault-gouge material properties (e.g., solid solubility, activation volume), microstructural parameters (grain size, porosity, shear band thickness), and experimental conditions (temperature, effective normal stress, imposed slip rate) (Chen et al., 2017). This shows that d_c scales with shear band thickness but varies (consistent with Marone and Kilgore, 1993) while varying only slightly with slip velocity, whereas and that the equivalent slip distance in response to large perturbations (d_p), increases with the size of the velocity perturbation (Fig. 8a). Using the CNS model as a basis, Van den Ende et al. (2018) showed that the process zone size (h_{cr}) for a propagating rupture can be expressed as $h_{cr} = d_c G / b \sigma_n$, where G is the shear modulus of the elastic medium. This result is consistent with the process zone size or 'nucleation length' L_0 derived from RSF analyses (Rubin and Ampuero, 2005). The common foundation of similarities between the RSF and CNS models becomes even more apparent when using applying classical fault stability theory (see eq. 4-) (Ruina, 1983; Gu et al., 1984). In the CNS model, specifically, varying the stiffness K enables simulation of a wide range of transient frictional behaviors frequently seen in laboratory experiments (Chen and Niemeijer, 2017; Baumberger et al., 1994; Leeman et al., 2016), including stable sliding, healing, attenuating or self-sustained (quasi-static) oscillations, and stick-slip (Fig. 8b) (cf. Baumberger et al., 1994; Leeman et al., 2016) (Chen and Niemeijer, 2017). The transition from stable to unstable behavior occurs at the critical stiffness $K = K_c$. The model similarly implies that the transition at low shearing rates, from fully ductile v -strengthening behavior to dilatant v -weakening (first peak in Fig. 7c) marks the point at which v -weakening causes acceleration, and ultimately, a fully dynamic instability (second peak in Fig. 7c).

Interestingly, periodic stick-slip of the type predicted by oscillations generated using the CNS model can also be reproduced by using numerical discrete element modelling (DEM) of gouges subject to direct-shear deformation that is, accommodated by concurrent granular flow and intergranular pressure solution (IPS) (Van den Ende and Niemeijer, 2018). Even though the detailed mechanics and assumptions used in DEM are dramatically different from those underlying the CNS approach model, the concept of shear strain accommodation involving a competition between dilatant granular flow and IPS seems sufficiently robust to reproduce a wide range of frictional sliding modes.

6 Earthquake cycle simulations using the CNS model

6.1 Empirical and physically-based earthquake cycle simulations

Laboratory observations of fault rock deformation are essentially can be thought of as measurements of a point along a fault that is characterized by a certain state of stress and thermodynamic conditions. Analytical models such as the CNS model offer a quantitative description of the mechanical behavior of the fault at that point. Numerical simulations are indispensable for up-scaling these 'point measurements' to the scale of the Earth's crust. In simulations of earthquake rupture nucleation and dynamic propagation, a section of crust or fault is usually discretized such that the continuum is represented by a collection of

points, the behavior of each of which is described ~~by~~with a constitutive relation. Over the last few decades, the rate-and-state friction model has been the preferred choice for numerical simulations of fault slip (~~e.g., Tse and Riee, 1986; Lapusta and Riee, 2003; Thomas et al., 2014; Luo and Ampuero, 2018~~). ~~Analyses of these simulations, which~~ has led to important insights into the spectrum of fault slip behavior (Shibazaki, 2003; Hawthorne and Rubin, 2013), earthquake rupture propagation and arrest (Tinti et al., 2005; Noda and Lapusta, 2013; Lui and Lapusta, 2016), and the relation between the earthquake source and seismological and geodetic observations (Kaneko et al., 2010; Thomas et al., 2017; Barbot, 2019; Ulrich et al., 2019). ~~A~~However, a major challenge that remains, ~~however,~~ is relating laboratory data of RSF parameters to fault rheology at depth in Earth's crust.

Physics-based models for fault-slip such as the CNS model provide a transparent origin of the constitutive parameters used, so that when employed in numerical simulations, a substantial portion of epistemic uncertainty is eliminated. Conveniently, in the case of the CNS model, its numerical implementation into a seismic cycle simulator (QDYN in the study of Van den Ende et al., 2018; ~~see Luo et al., 2017~~) is similar to that of the RSF equations, implying that it is compatible with existing codes for seismic cycle and dynamic rupture simulations. Furthermore, the modular nature of the CNS model enables specific micro-scale deformation mechanisms to be incorporated, based on microstructural observations of lab-deformed and natural samples. ~~It therefore more closely approaches 'reality', while,~~ offering a framework for studying the interaction between time-sensitive and -insensitive deformation mechanisms (i.e., ~~resp. creep and granular flow~~) that operate in the fault core — as frequently identified from field observations (e.g., Jefferies et al., 2006; Takeshita and El-Fakharani, 2013; Wallis et al., 2015). ~~creep and granular flow~~). That said, more work is needed to learn on, and quantitatively capture, the microphysical processes controlling deformation across the entire fault slip velocity spectrum, covering quasi-static deformation in interseismic periods as well as dynamic rupture.

6.2 Insights into the physics of fault behavior from CNS-based simulations

Because the dynamics of the CNS model are different from rate-and-state-friction (RSF), CNS-based numerical simulations of fault ~~deformation~~slip may lead to new insights into the physics of fault deformation. ~~An example is given by Van den Ende et al. (2018), who reported on~~ In a comparison between CNSRSF- and RSFCNS-based seismic cycle simulations. ~~One of their main findings was that even though, Van den Ende et al. (2018) found that~~ fault strength evolution near steady-state is practically identical, ~~but that~~ the behavior far from steady-state ~~is dissimilar, which points to~~ differs, ~~hence~~ differences in the ~~predicted~~between seismic cycle ~~behavior~~predictions. Specifically, in the absence of high-velocity dynamic weakening mechanisms, instead of producing seismic events with large co-seismic slip as expected from RSF-based simulations, CNS-based simulations produce ~~slow-slip events or~~ earthquakes with limited co-seismic displacement (Fig. 9). ~~This~~The latter can be explained by the transition from ν -weakening to -strengthening with increasing slip rate, ~~which is~~ implicit in the CNS model (see Fig. 7e). ~~This-7c~~, which effectively slows down dynamic rupture. In other words, the transition with increasing ν (or decreasing T) from ν -weakening to -strengthening, which has previously been speculated upon by Rubin (2011), emerges

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~~naturally from the CNS model, and has the effect of slowing down dynamic ruptures. This, then,~~ constitutes a potential mechanism for the generation of slow earthquakes (~~as previously speculated upon by Rubin (2011); see also Bürgmann, 2018) for a wide range of rheological parameters and boundary conditions.~~)

The emergence of slow ruptures in numerical simulations is closely related to the nucleation of a frictional instability, which, in the CNS model, occurs near the transition from the ductile creep regime (ν -strengthening) to the dilatant granular flow regime (ν -weakening) (Fig. 7c). In numerical simulations that employ classical RSF and an aging law (eqs. 1 and 2a), a rupture becomes dynamic when it exceeds a length scale that is proportional to the nucleation length L_b (Ampuero and Rubin, 2008; Rubin, 2008). When L_b approaches the size of the fault, the rupture is unable to fully accelerate to co-seismic slip rates, causing a slow slip event or slow earthquake (Rubin, 2008). For the CNS model, equivalent expressions for L_b can be obtained that apply to rupture nucleation near the ductile-frictional transition. However, in the case of a transition from ν -weakening to ν -strengthening, the transition from slow slip to fast slip is no longer accurately described by traditional estimates of the nucleation length using constant, rate-independent coefficients. Rather, a more detailed fracture mechanics approach (as adopted by Hawthorne & Rubin, 2013, for a modified RSF framework) may shed new light on the parameters controlling earthquake and slow slip nucleation, as well as of the thermodynamic and rheological conditions that control the spectrum of slip modes observed in nature.

Another example that highlights the major benefits of using a physically-based constitutive relation in numerical simulations is in studies of fluid-pressure stimulation of faults- (see Van den Ende et al., 2020, this volume). In the case of fluid injection or extraction, the change of hydrological properties with time is crucial for modelling thermo-hydro-mechanical coupling in the system. For the RSF framework, empirical formulae have been proposed aimed at describing that describe the relation between volumetric deformation and evolution of the state variable, θ (Segall and Rice, 1995; Shibazaki, 2005; Sleep, 2005; Samuelson et al., 2009). However, such a relation is not evident from the classical physical interpretation of θ as an asperity contact life-time. In the CNS model, gouge porosity assumes the role of the state parameter, implying that its evolution can be directly related to changes in fluid pressure, effective normal stress, and/ or hydrological properties within the fault (Van den Ende et al., 2019, 2020). To illustrate this, we simulate the evolution of porosity during nucleation, propagation, and arrest of a slow earthquake rupturing a one-dimensional fault with uniform frictional properties (Fig. 10), for the regime in which dynamic high-velocity slip is not yet triggered. During the nucleation stage, the fault dilates and weakens simultaneously with accelerated slip. As the rupture reaches its peak slip rates, the gouge attains maximum dilatancy and minimum strength, after which the gouge compacts upon deceleration and rupture arrest. During this cycle of nucleation, propagation, and arrest, the hydrological properties (i.e., hydraulic conductivity) can be computed based on the local porosity. In turn, and informed by laboratory experiments, this enables investigation of the dynamic coupling between fluid flow and fault slip (e.g., Cappa et al., 2019).

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7 Remaining challenges

To date, the microphysical and earthquake cycle modelling work described above mainly focused on the inter-seismic and nucleation stages of the seismic cycle. For a complete and self-consistent description of fault deformation, co-seismic slip rates must be considered as well. ~~The~~However, the present model assumptions are reasonable for gouge shear deformation at low slip rates, but break down when frictional heating and associated dynamic fault rupture processes come into play. Specifically, the model requires adaption to include heat production during deformation at ultra-high shear strain rates ($>>100\text{ s}^{-1}$), capable of triggering weakening processes such as thermal pressurization, decomposition, or melting (Rice, 2006; Di Toro et al., 2006, 2011; Platt et al., 2015). As described earlier in this paper, a first step in this direction has been made by Chen et al. (2019), who take into account slip rate-dependent heat production coupled with temperature and grain size sensitivity of creep processes (see Fig. 7c) (cf. De Paola et al., 2015; Pozzi et al., 2019).

Another major challenge yet to be addressed in fault deformation models lies in capturing the dynamics of micro- and nanostructure formation in sheared fault rock. The CNS model adopts a constant granular structure (Fig. 6), implying that the thickness of the deforming zone, and the grain size within, must be defined a priori. This is problematic for example under conditions close to the transition with increasing strain rate or decreasing temperature from ν -strengthening to ν -weakening (ref. Fig. 7c). ~~Constant- ν -Microstructures from~~ experiments on simulated calcite gouge ~~conducted at 550 high temperatures (500-600 °C showed that this transition is characterized by progressive shear strain localization from relatively distributed flow involving creep) point to the role of microcrystalline bulk gouge grains to granular flow grain growth, in localized bands, involving much finer grains (<1 μm , see Chen et al., 2020a). Ideally, shear strain localization and addition to grain size reduction are incorporated into a single, fully coupled gouge shear deformation model.~~

~~Adequate modelling, suggestive of granular system dynamics brings with trade-offs between grain size, temperature, slip velocity, and localization (Verberne et al., 2015, 2017). Moreover, there is~~ the additional complexity that the deformation properties of individual mineral particles can change with changing particle size. Constraining this is especially important in the case of nanometric gouge (grain size $<100\text{ nm}$), which, along with (partly) amorphized host rocks, are widespread in natural and experimentally-sheared fault gouges (Power and Tullis, 1989; Yund et al., 1990; for a recent review see Verberne et al., 2019). Individual nanoparticles and nanocrystalline aggregates frequently exhibit dramatically different physical properties compared with their bulk counter-parts (e.g., Meyers et al., 2006; Hochella et al., 2019) —the room temperature ductile nanofibers encountered in calcite gouge being an example of this (Fig. 5c-inset) (Verberne et al., 2014b, 2019). The implication is that extrapolation of data from compaction experiments using micron-sized crystals or larger, used to constrain parameter values appearing in the CNS model, may lead to large errors when applied to nanogranular or (partly) amorphous fault rock.

Even when coarser grained fault ~~gouges~~rocks are considered, frictional sliding on the contact between two grains is ultimately governed by nanometer-scale processes. This can either be envisioned as lattice-scale, solid-solid interactions for “dry” contacts or contacts with incomplete coatings of adsorbed species such as water (~~such as used~~ in the CNS model - Chen and Spiers, 2016), or as interactions arising from the unique properties of fully developed, adsorbed water or hydration layers

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475 (Leng and Cummings, 2006; Sakuma et al., 2018). Since the nanometric realm is inaccessible by standard observation techniques, directly probing the processes leading to grain-scale friction remains challenging, in particular for the LVF tests described in Section 3. Instead, Atomic Force Microscopy (AFM) experiments, also known as Friction Force Microscopy (FFM; see Bennewitz, 2005 for a review), may provide critical observations of the sample response to variations in sliding rate, normal stress, and chemical environment (Diao and Espinosa-Marzal, 2018, 2019). These observations will inform nanophysical models in a similar way as grain- and aggregate-scale observations have informed the CNS model. Finally, we note that the capability of the CNS model to fully describe the frictional behavior of strongly heterogeneous gouge compositions, including transients, remains to be investigated. ~~Presently, To date~~ this has only been demonstrated for monomineralic calcite (Chen and Spiers, 2016; Chen et al., 2017, 2020a). ~~However, in 2020~~. In the case that phyllosilicates constitute large portions of the fault gouge the overall constitutive behavior can no longer be represented by taking bulk mean values of rheological properties (pressure solution kinetics, grain size, etc.). Instead, the interactions between the various phases within the gouge need to be considered more closely, in the assumed microphysical model geometry (~~Den Hartog and Spiers, 2014—see e.g., Fig. 4b~~), or else using numerical simulations that enable aggregate heterogeneity (~~i.e., using discrete or finite element modelling such as Van den Ende and Niemeijer, 2018; models, see resp.~~ Wang et al., 2019 ~~or finite element methods such as~~; Beall et al., 2019). While microphysical modelling of heterogeneous systems poses some challenges, its potential outcomes likely offer new insights on natural fault deformation, including on the problem of upscaling to more realistic fault geometries (~~see e.g., Stenvall et al., 2019~~).

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8 Conclusions

We reviewed experimental and microphysical modelling work on the physics of low-velocity fault friction processes, carried out at Utrecht University (UU) since the early 2000's. Data from shear deformation experiments on simulated fault rocks composed of halite-phyllosilicate and phyllosilicate-quartz mixtures, and of monomineralic calcite, consistently show that fault gouge strength and stability is controlled by a competition between rate-sensitive creep and rate-insensitive granular flow processes. Under conditions where ductile deformation occurs in Earth's crust, fault shear deformation is non-dilatant and controlled purely by creep, which is intrinsically stable. However, towards shallower depths, frictional(-viscous) deformation occurs, which is controlled by creep of individual mineral grains operating alongside dilatant granular flow. The seismogenic zone represents a depth interval in the crust where these processes operate at comparable rates, $|\dot{\epsilon}_{dil}| \approx |\dot{\epsilon}_{cp}|$, which leads to velocity weakening hence seismogenic fault-slip behavior. This conceptual model framework is quantitatively described by the Chen-Niemeijer-Spiers (CNS) model for shear of gouge-filled faults, which constitutes a physically-based microphysical model that is capable of reproducing a wide range of (transient) frictional behaviors. ~~Implemented into numerical codes for fault rupture~~ Despite numerous challenges ahead on capturing deformation process active in slipping gouge-filled faults, including at co-seismic slip rates, the CNS model offers new, microstructurally and physically founded input for earthquake cycle simulators, and therewith new scope for the interpretation of earthquake source processes.

Availability of data and materials

All data are available from the papers cited, or else upon request from the corresponding author. The QDYN seismic cycle simulator (including the implementation of the CNS model) is open-source available from <https://github.com/ydluo/qdyn>.

510 Competing interests

The authors declare no conflicts of interest.

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Author contributions

BAV led the effort, drafted the initial manuscript, and wrote sections 1 and 3. BAV and MPAvdE co-wrote sections 2, 4, 7, and 8, with contributions by JC to section 4. JC wrote section 5, and MPAvdE section 6. ~~All authors contributed to writing~~ ~~of~~ARN and CJS helped through discussions and improved the final manuscript.

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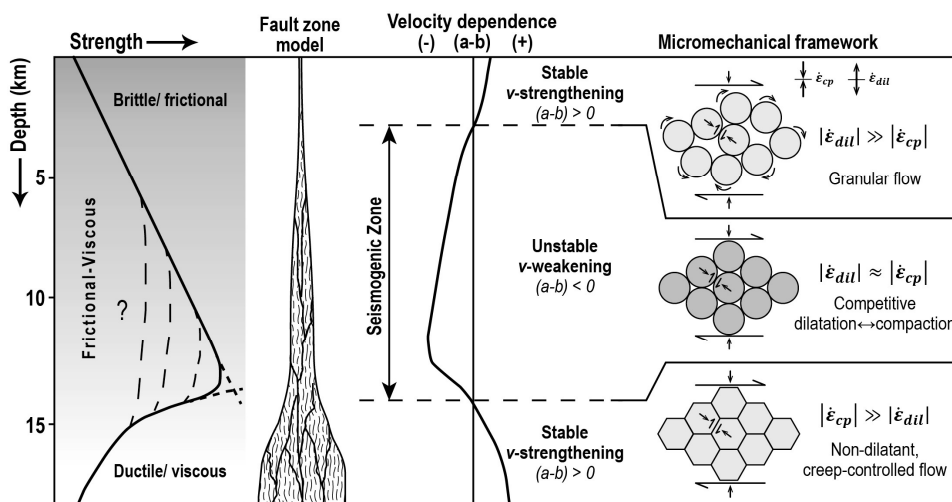
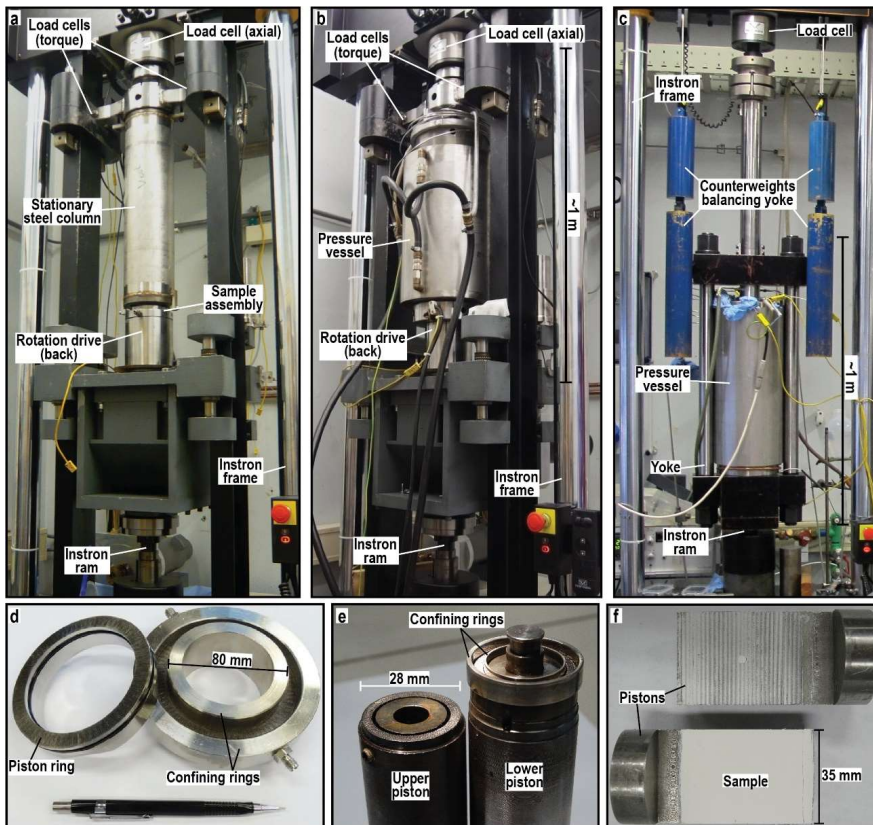


Figure 1. Conceptual model for an upper-crustal fault zone, **which highlights** the frictional-to-viscous transition and the seismogenic zone, **which is** characterized by **v-weakening** friction (i.e., $(a-b) < 0$). After Sibson (1982, 1983) and Scholz (1988, 2019). On the far right we summarize implications from **a micromechanical** the "CNS" model for shear of gouge-filled faults **that is based on, involving** a competition between creep-controlled compaction and dilatation by granular flow (occurring **resp.** at rates of **resp.** $\dot{\epsilon}_{cp}$ and $\dot{\epsilon}_{gr}$). For **model** details **on this model** see Bos and Spiers (2002a), Niemeijer and Spiers (2006, 2007), and Chen and Spiers (2016).

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935 **Figure 2.** Apparatuses and testing assemblies used for low-velocity, ring- and direct-shear friction experiments at UU. a) and d) the room temperature ring-shear set-up. b and e) the hydrothermal ring-shear set-up. c and f) the direct-shear set-up, using a triaxial pressure cell (in this case the “shuttle vessel”). Photo (a) by courtesy of **MikiM. Takahashi** (**Geological Survey of Japan**). Photo (d) taken with publishers’ permission from Van den Ende and Niemeijer (2019).

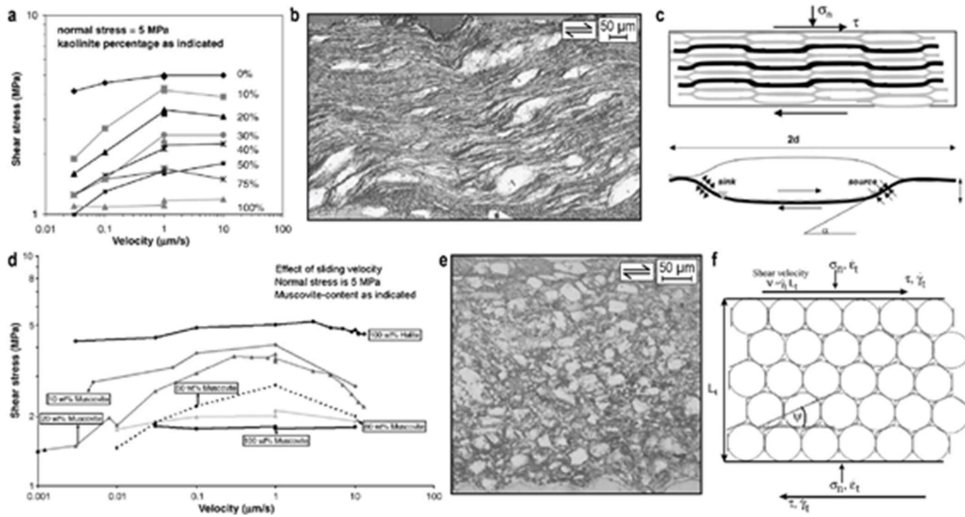


Figure 3. Key results from room-temperature ring-shear experiments on halite-phyllsilicate mixtures, conducted at room temperature. a) Velocity (v)-strengthening of halite and b) Halite-kaolinite gouges, and b) micrograph of a sample mixtures deformed in the v -strengthening, frictional-viscous regime (both from Bos et al., 2000b). c) Model framework of microstructure capturing v -strengthening, frictional-viscous flow (Bos and Spiers, 2002a). σ_n = normal stress; τ = shear stress; α = the angle between the leading edge of the halite grain and the horizontal; h = amplitude of the foliation; d = grain size (long axis). d) Velocity-dependence effects in halite-muscovite gouges (from Niemeijer and Spiers, 2006), with e) Micrograph of a sample deformed in the v -weakening regime (from Niemeijer and Spiers, 2005). d) Model framework of microstructure capturing v -weakening granular flow (Niemeijer and Spiers, 2007). $\dot{\epsilon}_t$ = macroscopic normal strain rate; $\dot{\gamma}_t$ = macroscopic shear strain rate; ψ = dilatation angle; L_t = thickness of the deforming zone; other symbols the same as in c). All images are taken with publishers' permission.

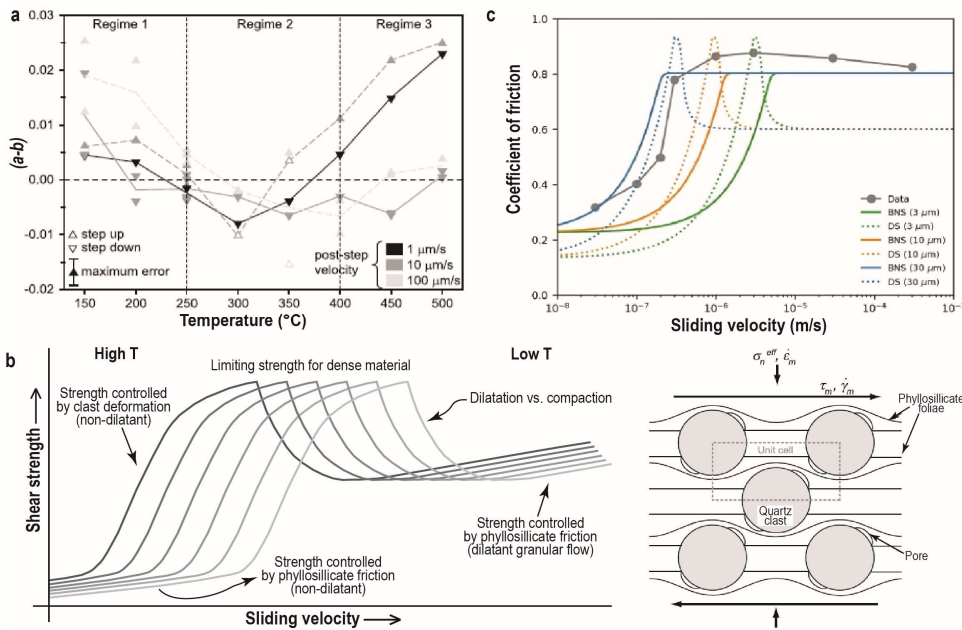


Figure 4. **Key results**Data from hydrothermal ring-shear experiments on quartz-phyllisilicate mixtures. a) Three-regimes of v -dependence seen in experiments on illite-quartz mixtures (~~from~~ Den Hartog and Spiers, 2014) ~~–~~ b) **Interpretation**Conceptual interpretation of quartz-phyllisilicate strength evolution with sliding velocity/ temperature (after left) (Den Hartog and Spiers, 2013). ~~The right-hand side shows~~, and the model microstructure envisioned by Den Hartog and Spiers (2014) (DS model, right). c) **Plot of the coefficient**Coefficient of friction at steady-state against sliding velocity **with including** data from constant- v experiments by Niemeijer (2018). ~~Curves show results of model calculations~~ in grey. The coloured curves are generated using the model for frictional-viscous deformation by (BNS, solid lines) (Bos and Spiers, 2002a ~~and~~; Niemeijer and Spiers, 2005), and using the DS model, (dashed lines), for different nominal grain sizes as indicated. The peaks mark a transition from v -strengthening to v -weakening. All images are taken with publishers' permission.

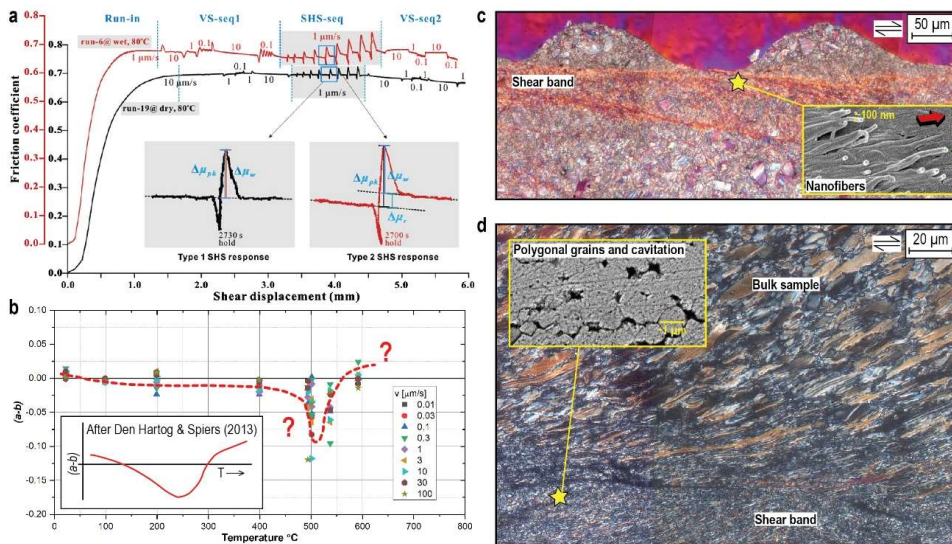


Figure 5. Key results Data from shear experiments on simulated calcite fault gouge. **a) Velocity** Direct-shear tests conducted at an effective normal stress (σ_n^{eff}) of 50 MPa, at 80 °C, under lab-dry conditions (black curve) and using a pore fluid pressure of 10 MPa (red curve). The test includes velocity-stepping (VS) and slide-hold-slide (SHS) experiments (from sequences; $\Delta\mu_r$ indicates residual healing after a hold period (Chen et al., 2015b)). **b) Data from v-stepping** Velocity dependence ($a-b$) against temperature for experiments performed conducted up to 600 °C at $\sigma_n^{eff} = 50$ MPa using the hydrothermal ring shear set-up (Verberne et al., 2015). **c and d)** Cross-polarized, transmitted light micrographs of samples sheared in v-stepping experiments conducted nominally dry at room temperature v-stepping experiments (c), and wet at 500°C (d) (from Verberne et al., 2013, 2015). Inset in (c) shows nanofibers observed on split sample fragments after an experiment. Inset in (d) highlights cavitated arrays of polygonal grains observed in a shear bands developed at high temperatures. All images taken with publishers' permission.

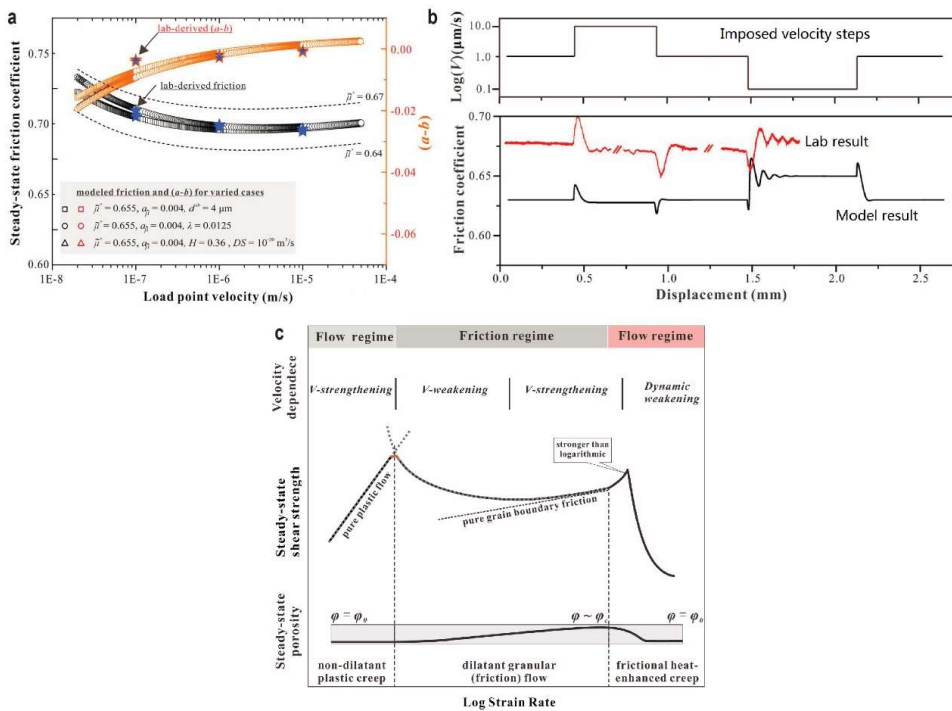


Figure 7. Examples of CNS model output. Reproduction of experimental data using the CNS model. a) steady-state frictional strength and (a-b) values, and b) v -stepping tests, of data from experiments on calcite gouge performed at $T = 80^\circ\text{C}$ and $\sigma_n^{\text{eff}} = 50 \text{ MPa}$ (see Fig. 5a, (Chen et al., 2015b)). c) Model output for over a wide range of fault sliding rates, highlighting a flow-to-friction transition with increasing v (see Chen et al., 2020a).

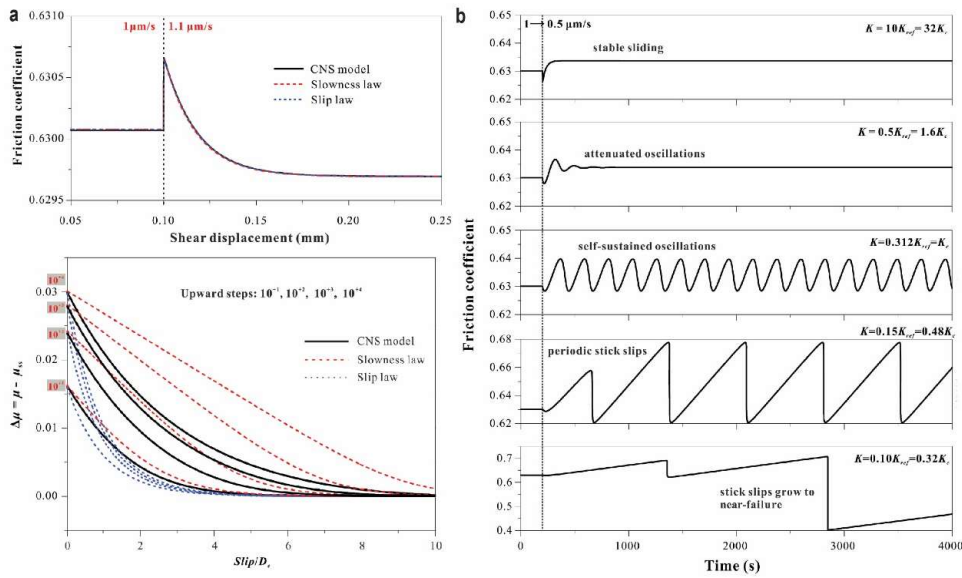


Figure 8. CNS modelling results. a) Comparison withbetween CNS- and RSF-model for small-based models. a) Small (1→1.1 $\mu\text{m/s}$) and large (up to 4 orders of magnitude) perturbations in sliding velocity (resp. the upper and lower diagrams). The RSF parameter values used are the equivalent values calculated from the CNS model (see Chen et al., 2017). b) CNS modelling of a velocity step 1→0.5 $\mu\text{m/s}$, for different stiffnesses K (see Chen and Niemeijer, 2017).

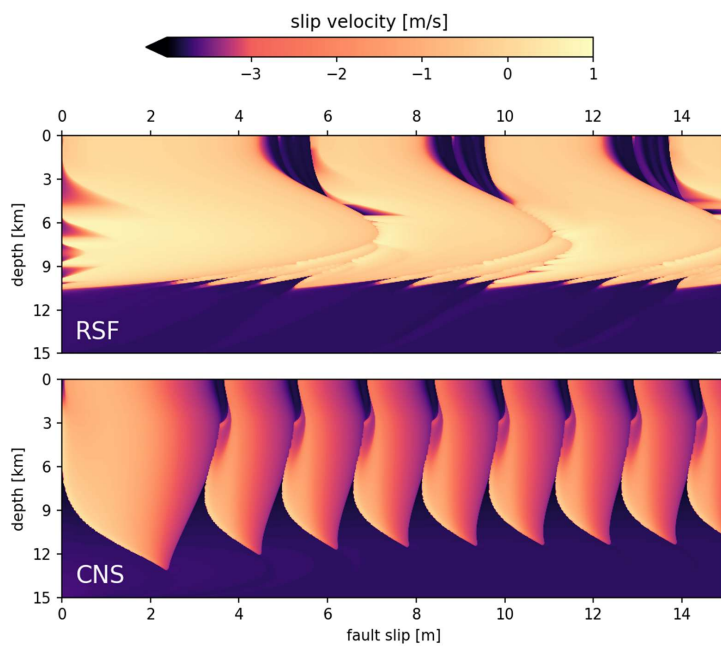


Figure 9. Numerical simulation of the spatio-temporal evolution of slip rates on a simulated strike-slip fault, based on rate-and-state friction (RSF; top), and on the Chen-Niemeijer-Spiers model (CNS; bottom). Brighter colours indicate higher slip rates, dark purple colours indicate slow creep. While the RSF-based simulation exhibits large and fast earthquakes, the CNS-based simulation exhibits mostly small slow slip events. After

Van den Ende et al. (2018).

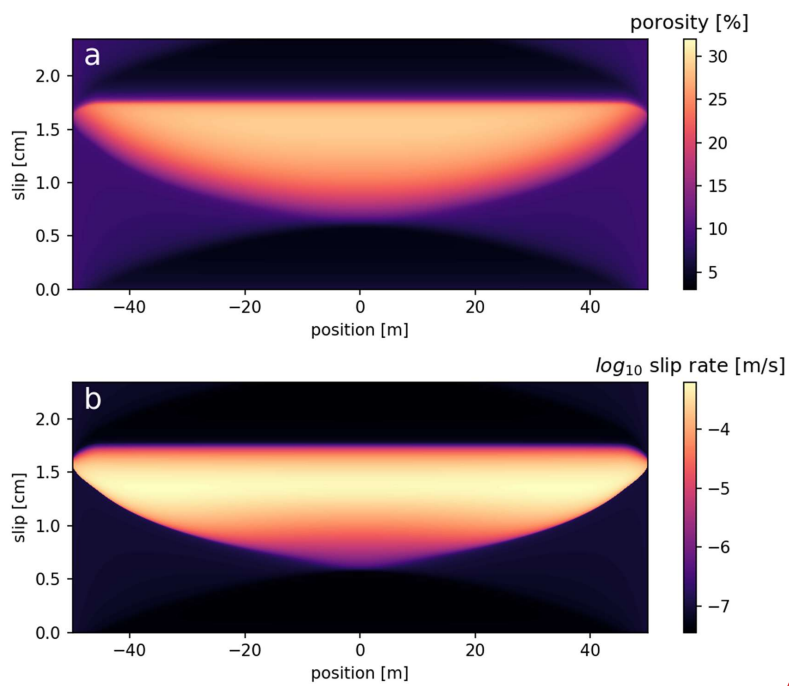


Figure 10. Spatiotemporal evolution of fault gouge porosity (a) and slip rate (b) during nucleation, propagation, and arrest of a rupture on a fault with uniform frictional properties. The rupture nucleates in the centre and propagates outwards.

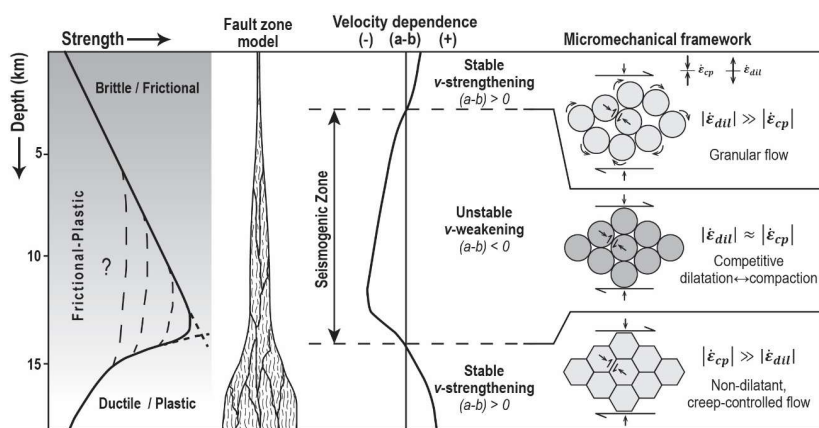
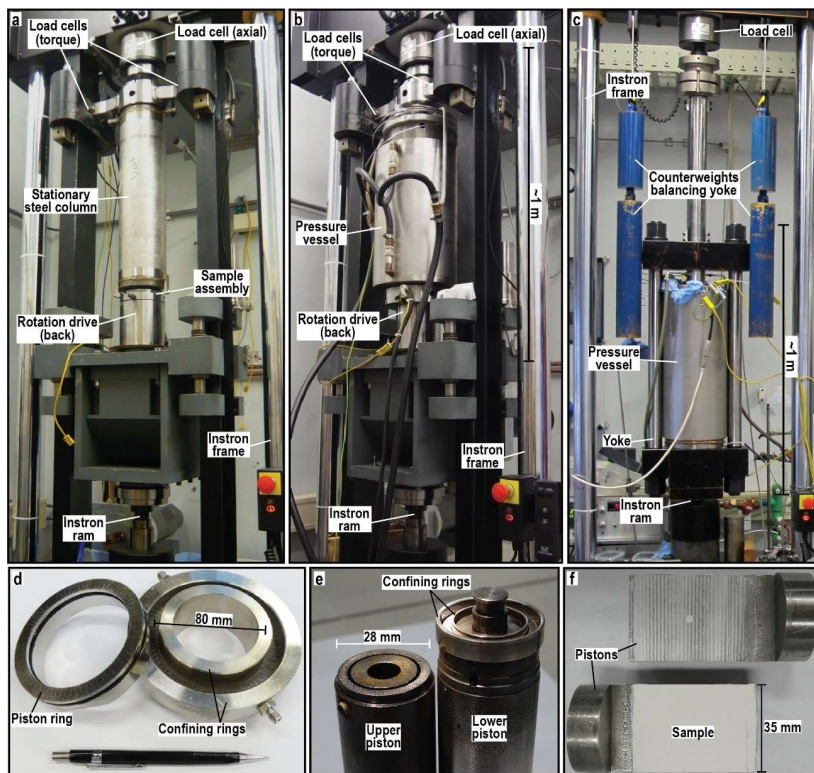


Figure 1



000 **Figure 2**

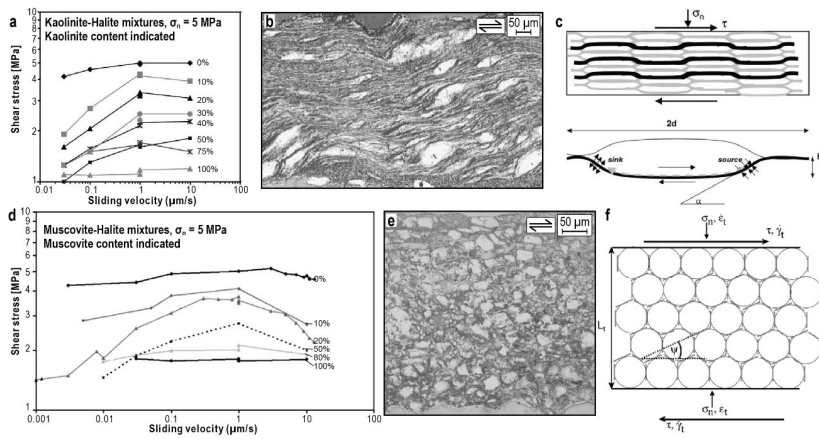


Figure 3

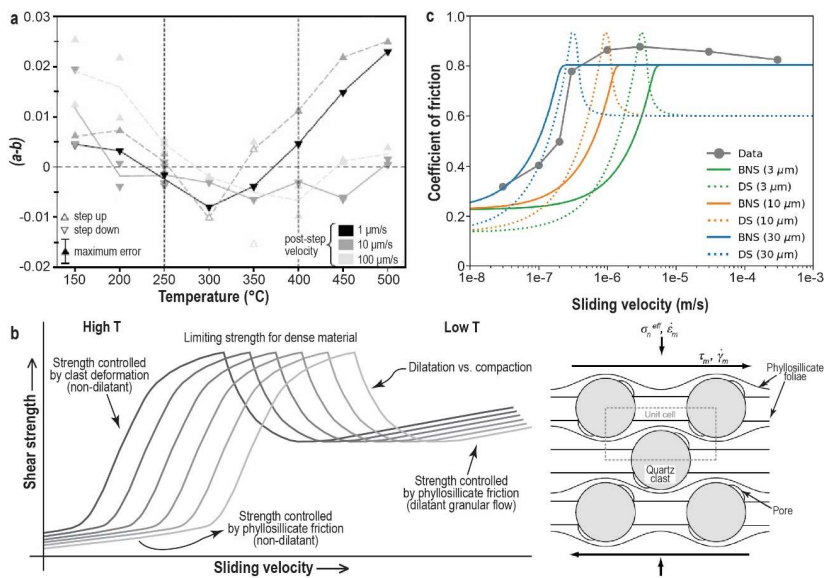


Figure 4

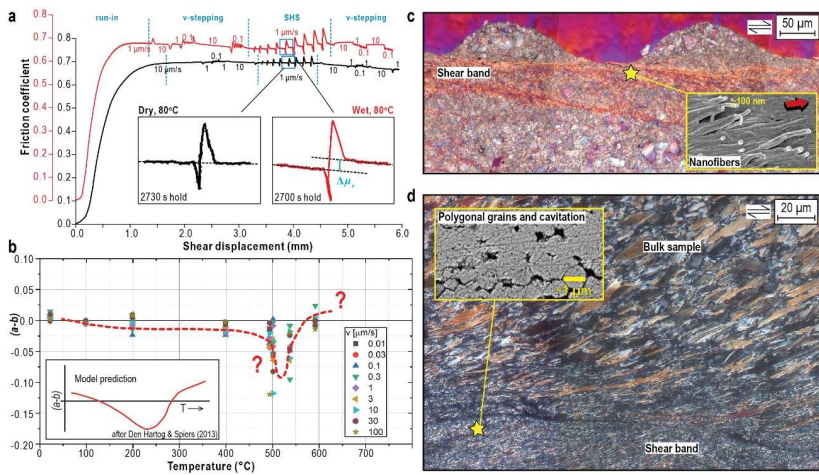


Figure 5

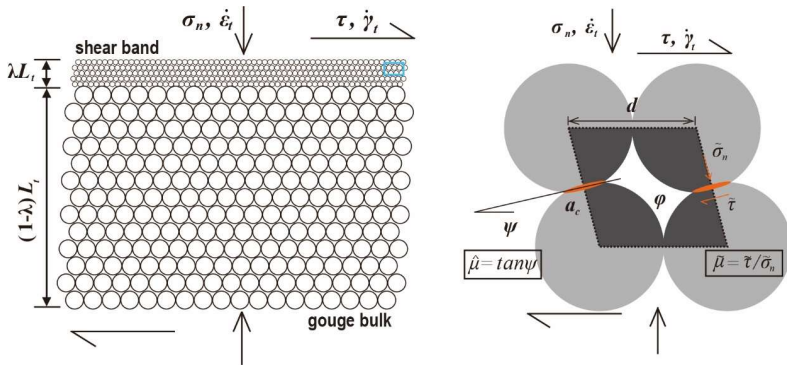


Figure 6

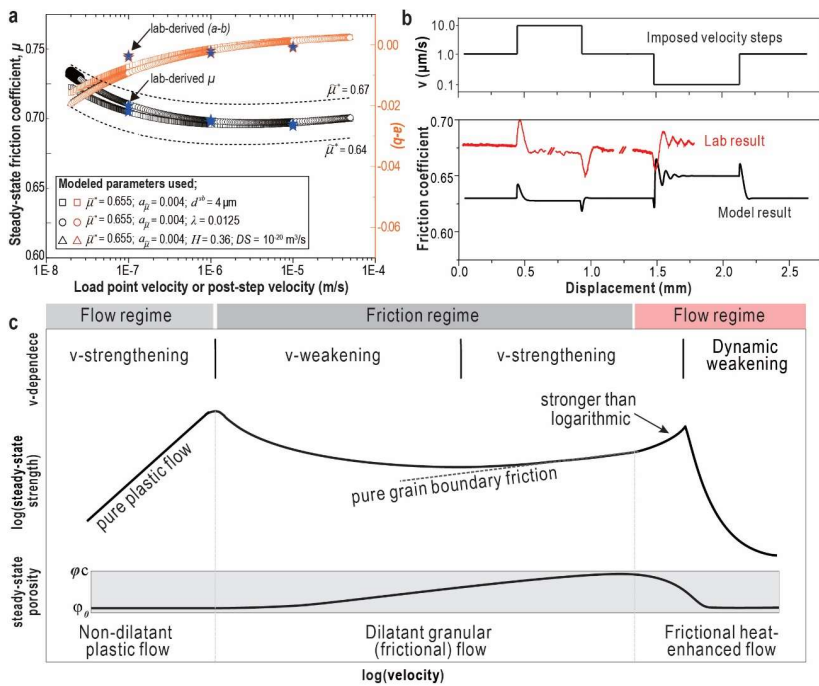


Figure 7

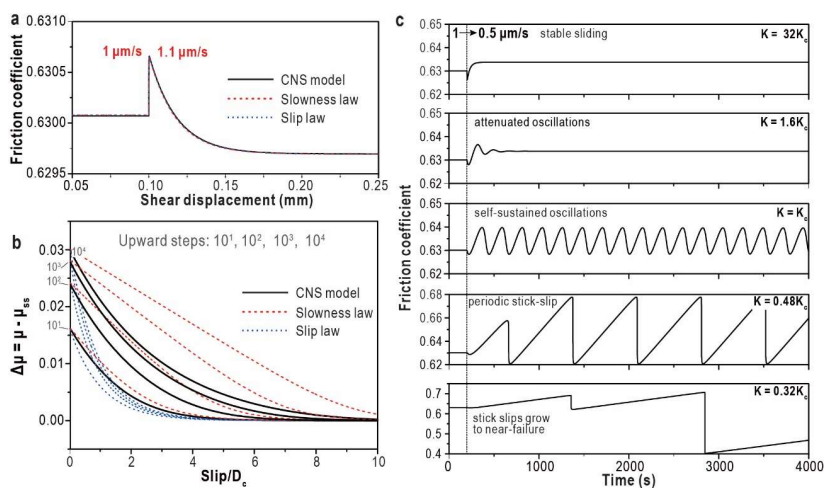


Figure 8

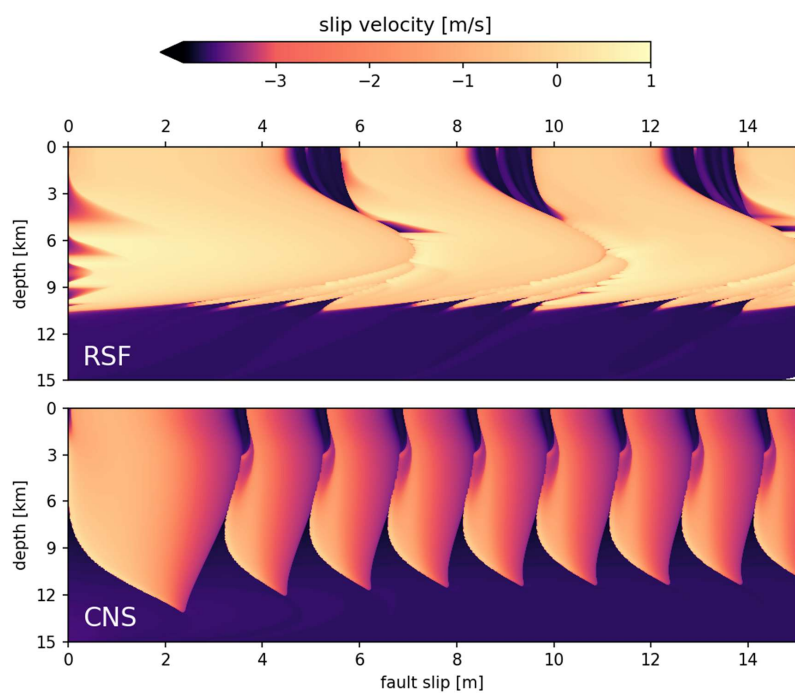


Figure 9

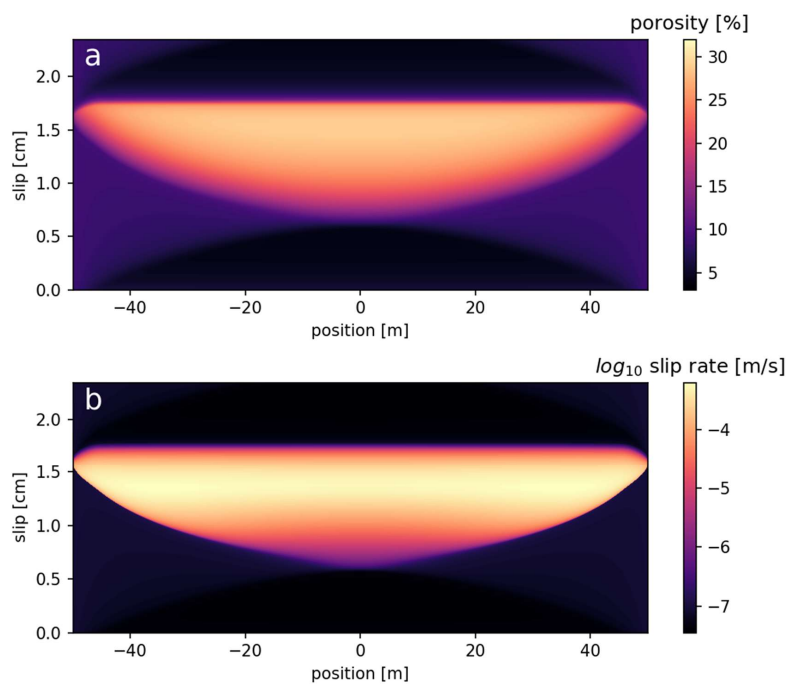


Figure 10