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Review

Inferring earthquake physics and chemistry using an integrated field and laboratory approach

André Niemeijer[a,b,*], Giulio Di Toro[b,c], W. Ashley Griffith[d], Andrea Bistacchi[e], Steven A.F. Smith[b], Stefan Nielsen[b]

[a] Faculty of Geosciences, Utrecht University, Budapestlaan 4, 3584 CD Utrecht, The Netherlands
[b] Istituto Nazionale di Geofisica e Vulcanologia, Via di Vigna Murata 605, 00143 Roma, Italy
[c] Dipartimento di Geoscienze, Università degli Studi di Padova, Via Gradenigo 6, 35131 Padova, Italy
[d] Department of Geology and Environmental Science, University of Akron, OH, USA
[e] Dipartimento di Geologia, Università di Milano Bicocca, Piazza della Scienza 4, 20126 Milano, Italy

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ABSTRACT

Earthquakes are the result of a combination of (1) physico-chemical processes operating in fault zones, which allow ruptures to nucleate and rock friction to decrease with increasing slip or slip rate, and (2) of the geometrical complexity of fault zones. In this review paper, we summarize recent experimental findings from high velocity (conducted at about 1 m/s slip rate, or typical seismic slip rates) rock friction experiments with an emphasis on potential dynamic weakening mechanisms (melt lubrication, nano-powder lubrication, etc.) and how these mechanisms might be recognized by means of microstructural and mineralogical studies in exhumed fault zones. We discuss how earthquake source parameters (coseismic fault strength, weakening distances, energy budgets, etc.) might be derived from the field and laboratory experiments. Additionally, we discuss what needs to be considered in terms of fault zone geometry and morphology (focusing on fault surface roughness) in order to develop models of realistic fault surfaces and present theoretical considerations for microphysical modeling of laboratory data at seismic slip rates, with an emphasis on the case of melt lubrication. All experimental data and, in the case of melt lubrication, microphysical models indicate that faults must be very weak ($\mu < 0.1$) during coseismic slip. Moreover, experiments have shown that the slip weakening distance during coseismic slip is on the order of a few tens of centimeters at most under natural conditions, consistent with inferences from field observations. Finally, we discuss open questions, future challenges and opportunities in the field of earthquake mechanics.

1. Introduction

Traditionally, earthquake mechanics have been investigated by the interpretation of seismic waves or by monitoring of active faults at the Earth's surface (e.g. Lee et al., 2002). However, these methods can only be used to infer relative stress changes during a seismic event and thus yield incomplete information about the earthquake source (e.g. the dynamic strength and energy budget remain poorly constrained, e.g. Kanamori and Brodsky, 2004). In addition, the physical and chemical processes that are active during the seismic cycle, which might explain why a certain mechanical evolution is observed, cannot be investigated with these methods.

In recent years, several drilling programs (e.g. the Nojima Fault in Japan, Boullier et al., 2001; the Chelungpu Fault in Taiwan, Ma et al., 2006; and the San Andreas Fault in the U.S.A., Ellsworth et al., 2000) have been undertaken to probe active faults. In addition to gaining direct information on fault composition and the possibility to extract samples for use in laboratory experiments, fault drilling allows for real-time monitoring of *in-situ* parameters such as strain rate and pore fluid pressure, and for sampling high-quality seismological data via downhole seismometers. However, the costs of fault drilling projects are typically high, the fault zone volume sampled is very small and the maximum depth that can currently be drilled is limited (3 km or so). Some similar data come from active faults found in deep mines (e.g. McGarr et al., 1975; Reches, 2006; Lucier et al., 2008; Heesakker et al., 2011a,b), but these datasets are even more scarce.

An alternative multi-disciplinary approach to understanding earthquake mechanics is to combine field geology, microstructural

* Corresponding author. Faculty of Geosciences, Utrecht University, Budapestlaan 4, 3584 CD Utrecht, The Netherlands.
E-mail addresses: a.r.niemeijer@uu.nl, niemeijer@geo.uu.nl (A. Niemeijer).

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observations, laboratory experiments and numerical modeling (a possible work-flow is outlined in Fig. 1). Field studies on exhumed fault zones (block A in Fig. 1) can establish whether seismic slip has occurred, based on the presence of pseudotachylytes for example (Sibson, 1975). Once this is established, the dominant deformation mechanisms within and surrounding the main slipping zones can be determined with the aid of careful microstructural and (micro) chemical analysis (block B in Fig. 1). Quantitative analysis of fault zone geometry, morphology and architecture using methods such as laser-scanning (Light Detection And Ranging; LIDAR), differential GPS and photogrammetry is necessary to provide input for large-scale numerical models (block D in Fig. 1). Experimental studies (block C in Fig. 1) that investigate the physical properties of the fault rocks, preferably under conditions that are close to those encountered in nature (i.e. σ_n up to ~200 MPa, slip velocities of 10^{-6}–1 m/s, "ambient" temperatures up to 400 °C and the presence of (hydrothermal) fluids at elevated pressure), can be used to constrain or calibrate microphysical or empirical constitutive equations for use in large-scale numerical models (block D in Fig. 1). At the same time, experimental microstructures can be compared to natural microstructures to verify that the active deformation mechanisms are similar. An ideal final step is to integrate data from experiments and natural exposures of faults to realize numerical models capable of generating artificial seismograms that can be directly compared to observations of actual earthquakes (block D in Fig. 1). We are still some way from realizing such a complex numerical model, but significant progress has been made in recent years (e.g. Dunham et al., 2011a,b). In the following sections, we summarize and discuss progress that has been made in each of the four panels depicted in Fig. 1, with an emphasis on the recognition of dynamic weakening mechanisms in the laboratory, potential seismic slip indicators in the field, and their use in inferring earthquake source parameters, and on the difficulties associated with extrapolation of laboratory data to natural conditions and upscaling to a realistic fault including geometrical complexity.

2. Dynamic weakening mechanisms in the laboratory

In the past two decades, the development of high velocity friction apparatuses has inspired a large number of experimental

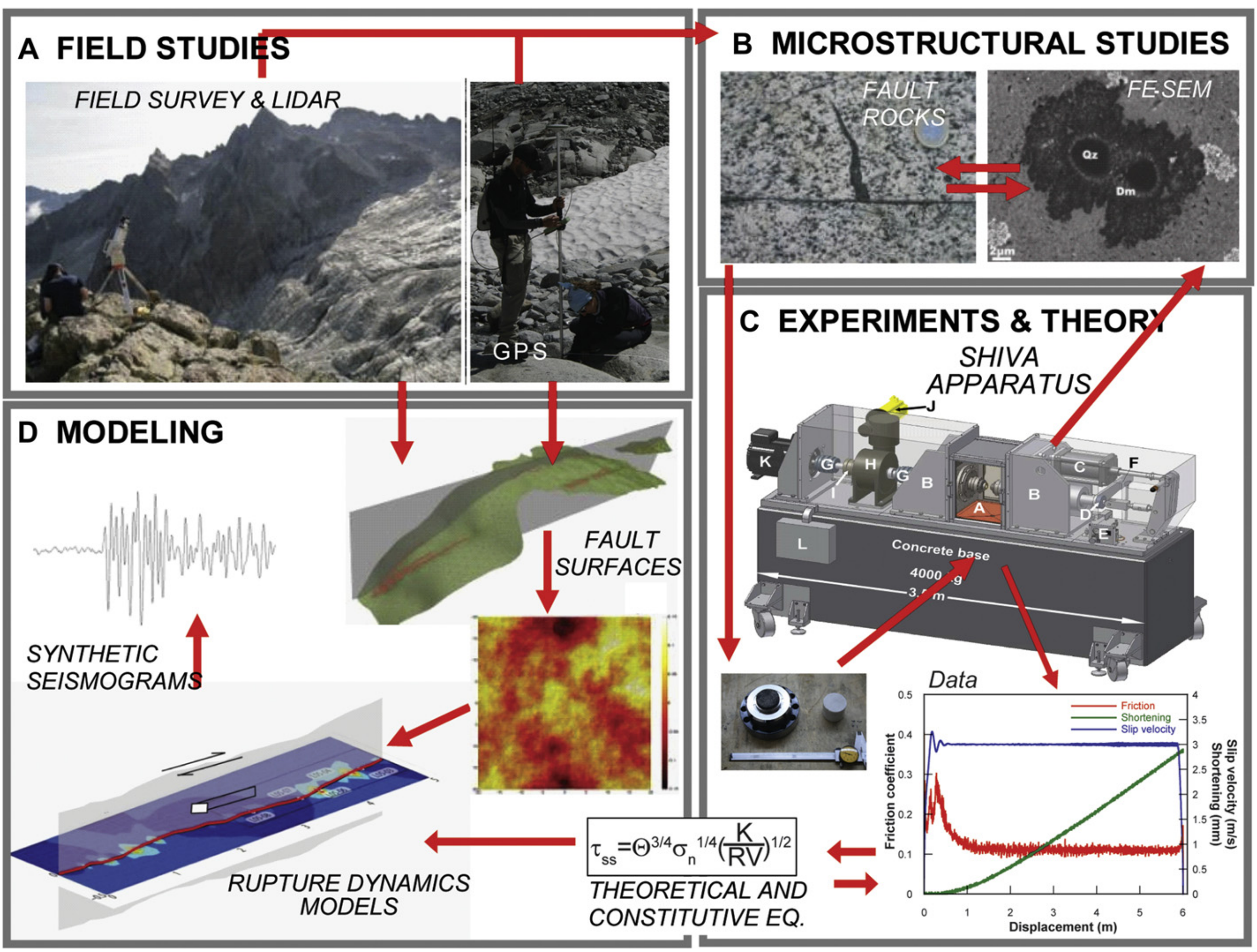

Fig. 1. Schematic diagram illustrating a multi-disciplinary integrated approach to understanding the earthquake machine: (a) Field studies of exhumed fault zones in order to verify and characterize the occurrence of ancient seismic slip and to determine the operating deformating mechanisms through (b) detailed microstructural and (micro)chemical analysis and to map the 3-dimensional geometry of the fault zone in detail and over a large range of scales to serve as input for (d) large-scale numerical models. (c) Systematic laboratory experiments to determine the microphysico-chemical processes that control the evolution of friction with slip combined with microstructural and (micro)chemical analyses of the experimental products to verify the operation of the same deformation mechanisms as in nature. Finally, the experimental results can be used to develop and test a microphysically based model which can then be used as input for (d) the large-scale numerical model, allowing dynamic simulations of the seismic cycle, producing as one of the output artificial ground motion records which can be compared with observations of real earthquakes.