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INTRODUCTION

Friction phenomena in rock: an introduction

JOHN G. SPRAY

Department of Geology, University of New Brunswick, Fredericton, Canada E3B 5A3

CONTENTS OF THE SPECIAL ISSUE

THE contents of this special issue are the outcome of a 3 day conference held at the Lord Beaverbrook Hotel in Fredericton on 24–26 August 1988, followed by a 1 day field trip in the Appalachian orogen of southern New Brunswick. The 11 papers cover aspects of rock friction based on theoretical considerations (Stesky & Hannan), laboratory experiments (Biegel *et al.*, Chester, Marone & Scholz, Morrow & Byerlee), field studies (Jordan & Nüesch, Magloughlin, Power & Tullis, Sibson) and possible seismogenic analogues (Glowka, Spray). A number of distinct approaches to rock friction studies are presented, although their bias is primarily geological rather than seismological. One of the objectives of the conference was to consider friction phenomena produced at high as well as low slip rates and this is reflected in the bipartite division adopted for the papers contained in this special issue.

SEISMIC FAULTING AND THE FRICTION RATE PARAMETER

The occurrence of natural friction phenomena as developed in geological materials is mainly restricted to the upper 10–15 km of the Earth's lithosphere. For a relatively undisturbed geothermal gradient it is well-established that this uppermost zone is defined by predominantly brittle deformation behaviour and also by earthquake activity. The transition between seismic and aseismic behaviour is defined by a zone, which may be several km thick, in which deformation takes place by a combination of co-seismic frictional sliding and inter-seismic non-brittle movement. It is within the brittle zone that earthquakes nucleate, but they may propagate from the brittle zone into the underlying semi-brittle zone (Scholz 1988, Shimamoto 1989).

The behaviour of a fault within the brittle and semi-brittle fields can be characterized by the so-called friction-rate parameter $a - b$, where a quantifies the *instantaneous* response of friction to a velocity change and b (the relaxation parameter) is the *steady-state* friction value for a velocity change (for details see Dieterich 1978, Rice & Ruina 1983, Ruina 1983). In the relatively low temperature (<300°C) brittle field, $a - b$ is negative and friction is velocity-weakening. This gives rise to abrasive wear, unstable sliding and stick–slip behaviour. For the semi-brittle field (*ca* 300–400°C), corresponding to the onset of plasticity in quartz, $a - b$ is positive and friction is velocity-strengthening. This leads to plastic flow, adhesive wear and more stable sliding, but still within a macroscopically frictional and, hence, potentially seismic regime. Termination of the semi-brittle field is demarked by essentially pressure-insensitive slip which is achieved by dislocation glide and various diffusion processes.

Laboratory experiments indicate that the friction-rate parameter is viable for relatively low slip rates and, as such, applies to Part I of this special issue. For example, the works of Biegel *et al.*, Marone & Scholz and Morrow & Byerlee, which consider gouge evolution, are concerned with essentially brittle-field effects where $a - b$ is negative; whereas the works of Chester and Jordan & Nüesch deal with brittle and semi-brittle phenomena where $a - b$ can be negative or positive. At higher slip rates (i.e. during co-seismic slip), the dependence of the frictional resistance on velocity becomes less apparent and some workers claim that friction becomes independent of velocity (e.g. Okubo & Dieterich 1986). The reasons for this are not yet clear, but the friction-rate parameter cannot be easily applied to the bulk of the works of Part II of this special issue (i.e. for the higher slip-rate effects).

LOWER AND HIGHER SLIP-RATE EFFECTS

The effects of faulting within the seismogenic zone result in wall rock modifications that include brecciation, cataclasis, mylonitization and melting. It is not the purpose here to review the classification and nomenclature of such fault rocks, this task has been attempted elsewhere (e.g. Sibson 1977, Wise *et al.* 1984). Rather, the aim is to focus on processes occurring under different conditions of faulting, whether for pre-, inter-, co- or post-seismic behaviour (i.e. slip-rate-dependent), or for the brittle or semi-brittle zones (i.e. depth-dependent).

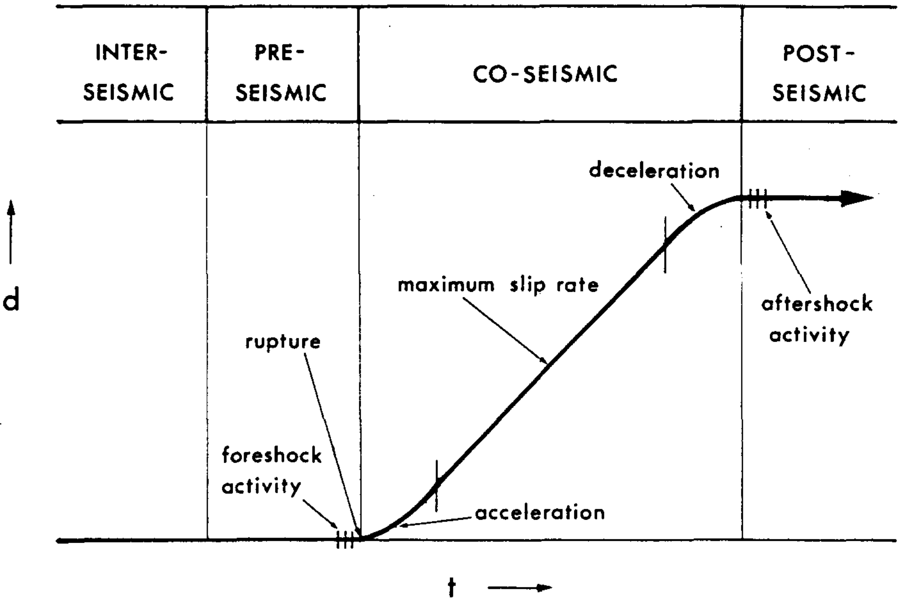

Fig. 1. Time (t) vs displacement (d) plot showing idealized particle velocity in a seismogenic fault. Part I of this special issue concerns processes that occur mainly during pre-, post- and inter-seismic periods, whilst Part II mostly covers processes occurring during co-seismic slip. Modified after Swanson *et al.* (1989).

However, in terms of broad associations, cataclastic rocks tend to be generated in the brittle field, whereas mylonitic rocks are typically formed in the semi-brittle to underlying non-brittle fields. Friction melts (i.e. certain pseudotachylytes) can be generated in either one of these two zones because their formation is primarily velocity- rather than depth-dependent.

A crude division of friction phenomena in fault zones can be made based on whether the effects are generated during or between earthquakes (Fig. 1). This approach is adopted for categorizing the collection of papers in this special issue. The first section discusses aspects of sliding rock surfaces within the brittle and semi-brittle fields at relatively low slip rates. In this category, frictional heating is negligible and cataclasis, gouge evolution and semi-brittle flow are the dominant processes. These low slip-rate phenomena correspond to post-, inter- or pre-seismic deformation. This equates with movement at or less than plate tectonic rates for natural faulting and somewhat faster than this for most laboratory experiments, but still at considerably less than co-seismic slip rates. The study of low slip-rate processes is critical for understanding premonitory slip and for earthquake prediction (e.g. Tullis 1988).

The second section covers aspects of sliding rock surfaces within the brittle and semi-brittle fields at high slip rates. In this case, frictional heating may become an important consideration, potentially resulting in a reduction in friction due to surface melting or pore fluid expansion (e.g. Mase & Smith 1987). The high slip-rate phenomena correspond to the co-seismic phase of deformation (i.e. slip rates of 0.1–2.0 m s^{-1}). The study of high slip-rate processes is important for relating earthquake magnitude to rock type and faulting conditions. In comparison with low slip-rate research, particularly as carried out in the laboratory, high slip-rate processes have received relatively little attention. Even though the study of low slip-rate phenomena may enable a degree of earthquake prediction to be achieved, the *magnitude* of a resulting earthquake is strongly governed by what happens *during* co-seismic slip. More research should therefore be directed at experimentally simulating the effects of displacements at high slip rates.

There are obvious drawbacks to using slip rate as a classification basis for fault rocks. This is because some fault rocks can be generated and continuously modified during periods of both low and high slip rates (e.g. slickensides). Their overall development is therefore linked to the seismic cycle as a whole (e.g. Power & Tullis). Furthermore, it is not known at exactly which stage of movement some types of fault rock are generated (e.g. gouge). These difficulties emphasize the *cyclical* nature of fault rock deformation and the problems of attributing any one effect to a specific phase of fault behaviour. Nevertheless, the ultimate objective is to relate friction effects to the earthquake cycle and, although we are far from being able to achieve this yet, this small collection of papers is hopefully a step in the right direction and is one that may form a stimulus for continued research along these lines.

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