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The contribution of structural geology, experimental rock deformation and numerical modelling to an improved understanding of the seismic cycle Preface to the Special Volume "Physico-chemical processes in seismic faults"

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Earthquakes are one of the world's most deadly geohazards, with an average annual death toll of 80,000 over the last decade alone (Bartels and VanRooyen, 2011). This death toll will likely increase still further during the 21st century given the forecasted growth in the global population. Seismic hazard maps (ground acceleration probability maps based on instrumental and historical earthquakes catalogues and rock acoustic transmission properties), as well as the strict application of building construction codes represent the most effective mediations to reduce earthquake damage and human casualties. In some settings, tsunami and earthquake early warning alert systems are additional powerful tools to save human lives (Gasperini et al., 2007). The deterministic prediction of an earthquake (i.e. mainshock hypocentre location, magnitude and time) remains the Holy Grail of Earth Sciences, and may be impossible to achieve (see Hough, 2010 for a review). However, promising earthquake forecasting models (i.e. determination of the probabilities that a seismic event will occur in terms of mainshock hypocentre location, magnitude and time) exist and are based on short-term earthquakes statistics (earthquake clustering, Omori law, Gutenberg-Richter law, etc.), and the inferred relationships between stress transfer and seismicity rate (Stein, 1999; Jordan et al., 2011). However, forecasting models need to be underpinned by physical constraints (fault geometry, coseismic slip distribution, friction laws, e.g. Tullis, 1988; Dieterich, 1994; Hainzl et al., 2010; Cocco et al., 2010). In this framework, an improved knowledge of the physico-chemical process active during the seismic cycle will inevitably contribute towards the better definition of physically based earthquake forecasting models.

Earthquakes are the result of rupture and friction processes (Scholz, 2002) and are major upper crustal deformation processes associated with geological faults (Sibson, 1989). Since destructive earthquakes nucleate at depth (7–25 km), direct access to modern seismic sources is impossible and most earthquake source studies are conducted using seismological and geophysical approaches (see Abercrombie et al., 2006; Lee et al., 2002 for reviews). Seismology can retrieve five main earthquake parameters from the analysis of seismic waves (Kanamori and Rivera, 2006):

- the seismic moment M_o;
- the static stress drop $\Delta\tau_s$;
- the radiated energy E_R;

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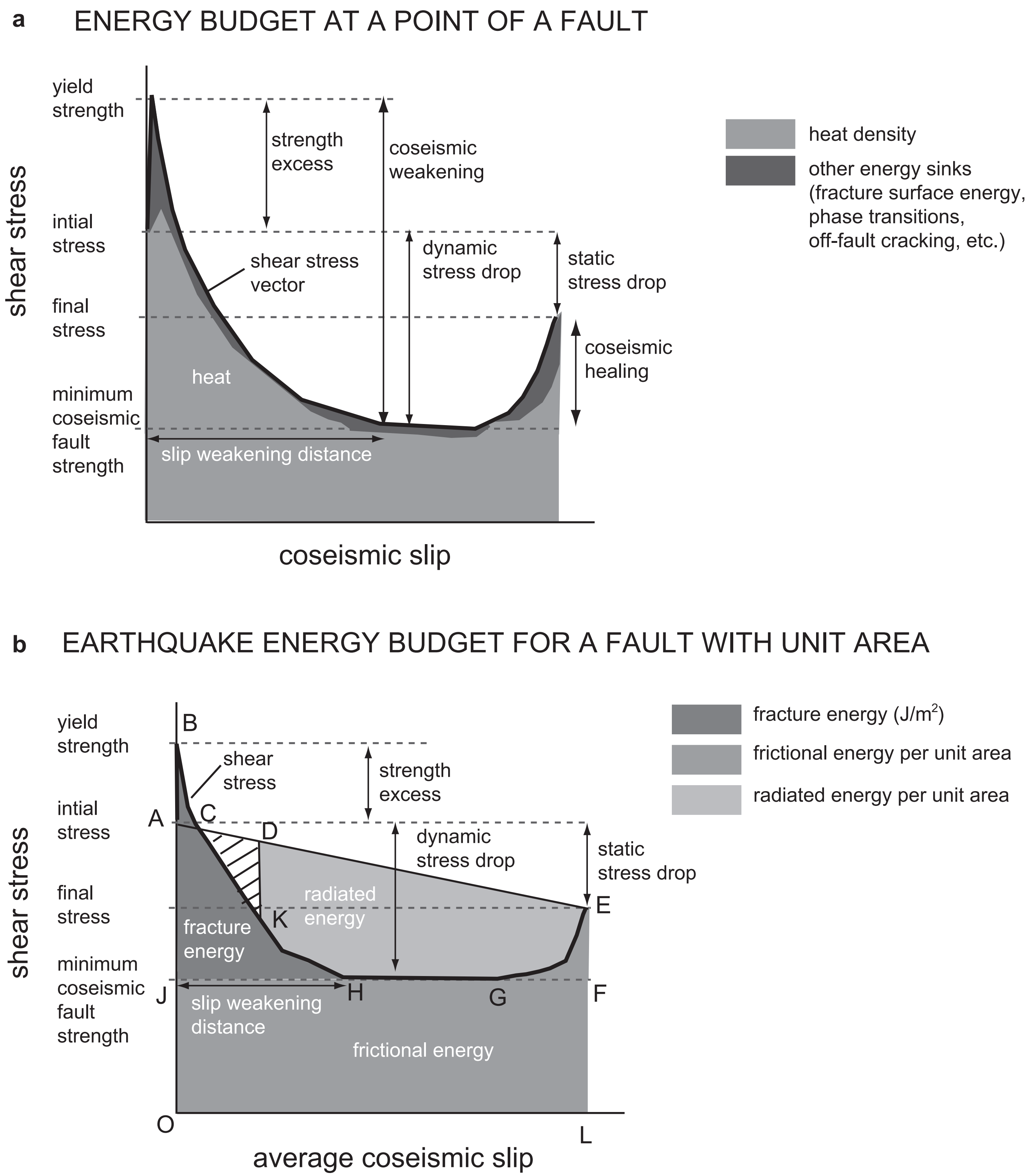

Fig. 1. Energy budgets during earthquakes. a) The energy budget and evolution of shear stress with coseismic slip at a single point along a fault. This diagram is similar to those obtained in high speed rock friction experiments (though experiments do not reproduce the dynamic stress field associated to the tip of the propagating rupture, Beeler, 2006). The shear stress coincides with coseismic fault strength once the yield strength is achieved at the passage of the rupture front. The diagram includes the definitions of static stress drop (difference between initial shear stress and final shear stress at the end of slip), dynamic stress drop (difference between initial shear stress and minimum fault strength), strength excess (difference between yield strength and initial shear stress – in the so-called "high-velocity" friction experiments the initial shear stress is zero), coseismic weakening (difference between yield strength and minimum shear stress) and coseismic healing (difference between final stress and minimum fault strength). The frictional work per unit area (area below the shear stress curve) is partitioned in heat density and fracture surface energy per unit area. The heat exchanged in seismic faulting determines the increase in temperature in the slipping zone and wall rocks. Fracture surface energy includes effects due to the formation of new grain surfaces during fracturing, phase transitions (e.g. solid to melt), off-fault cracking, etc. The slip weakening distance is the slip from initial shear stress to minimum coseismic fault strength. This diagram does not include radiated energy. To include radiated energy, the shear stress curve should be coupled to rupture and elasto-dynamic models including radiation and non-local interaction which is not considered here

- the rupture speed V_r and directivity;
- the fracture energy (sometimes called breakdown work W_b).

Importantly, however, fundamental information, including the absolute value of the shear stress and its evolution during slip, the energy partitioning during an earthquake, and more generally information that might constrain the physical processes acting on a fault during seismic slip, are beyond the capabilities of seismological investigations (Beeler, 2006) (see Fig. 1 for definitions). In addition, since the estimation of dynamic stress drop from inverse analysis of seismic waves is strongly model dependent, the determination of the slip weakening distance remains poorly constrained (Ide and Takeo, 1997; Fukuyama et al., 2003; Piatanesi et al., 2004) (Fig. 1). Seismological and geophysical observations such as the rupture speed and dynamics (self-healing pulses vs. crack-like, Heaton, 1990), the increase, though debated, of radiated energy with seismic moment (Kanamori and Heaton, 2000), large coseismic slips, strong ground motions, etc., might be explained by different physical and chemical processes active during seismic slip. The most popular include melt lubrication, thermal pressurization and flash heating and weakening (e.g. Kanamori and Heaton, 2000; Ma et al., 2003; Wibberley and Shimamoto, 2005; Rice, 2006; Noda and Lapusta, 2010a). However, the information that can be retrieved from seismic waves is limited by the resolution and clarity of the signal: given source effects (directivity and radiation pattern), path and site effects (attenuation and geometric spreading) that also cut off the high-frequency waves (Venkataraman et al., 2006), little can be said about the physical and chemical processes responsible for rupture nucleation and propagation (Beeler, 2006).

The complexity of the seismic cycle results from the non-linear and chaotic evolution with time of stress and fault strength (Kanamori and Brodsky, 2004) (Fig. 2). On human timescales at least (decades to millennia) the seemingly irregular occurrence of mainshocks along faults results from the combination and feedback between: (i) tectonic (and gravitational in some cases) stress loading rates plus stress perturbations (the latter might be almost abrupt: static and dynamic triggering, pore fluid migration, e.g. Byerlee, 1993; Stein, 1999; Gomberg et al., 2001; Johnson and Xiaoping, 2005; Miller et al., 2004); with (ii) relatively short- to long-living chemical and physical processes controlling fault zone strength (evolution of elastic properties of the fault zone with time, fault sealing vs. fault weakening processes, etc., e.g. Blanpied et al., 1992; Lockner and Byerlee, 1995; Wintsch et al., 1995; Miller et al., 1996; Olsen et al., 1998; Gratier et al., 2003, 2011; Tenthorey et al., 2003; Holdsworth, 2004; Li et al., 2006; Collettini et al., 2009; Mittempergher et al., 2011). The interaction between stress acting on a fault and fault strength is further complicated by coseismic processes (velocity-dependent weakening and strengthening, e.g. Sone and Shimamoto, 2009; Di Toro et al., 2011).

The lithological heterogeneity, fault zone and fracture network geometry, physical and chemical role(s) of fluids, rock physical properties (permeability, stiffness, etc.) are all ingredients that must be considered in a physically-based probabilistic fault forecasting model. The astonishing finding of non-volcanic tremor (low-frequency earthquakes) beneath locked and creeping sections of major seismogenic fault zones (Obara, 2002; Shelly, 2010) reminds us of the lack of knowledge about the coupling of the seismogenic upper crustal layer with the lower crust. The complexity of the seismic cycle is witnessed by the fact that the best monitored fault segment in the world (the San Andreas Fault at Parkfield) produced a moderate in size earthquake (Parkfield 2004, M_w 6.0) without any clearly recognized precursor events (Bakun et al., 2005) whereas, other faults (e.g. the North Anatolian Fault) probably ruptured (Izmit 1999, M_w 7.1) after a preceding accelerating creep phase in the nucleation area monitored at the surface with a much less sophisticated single one-component station (Bouchon et al., 2011). Whatever the case, without the knowledge of the processes activated during the seismic cycle, little can be said on earthquake physics and this makes any process-constrained earthquake forecasting model an almost impossible challenge to address.

A complementary approach to the study of earthquakes comes from field, experimental and theoretical investigations of fault zone and fault-related rocks: this approach is centred in the discipline of Structural Geology and includes elements of microtectonics, mineralogy/geochemistry, rock physics and numerical modelling (Fig. 3). Such geologically-based approach formed the inspiration behind the convening of a workshop on *Physico-chemical processes in seismic faults* held on the 18th–20th November 2010 at the Dipartimento di Geoscienze of Padua University (Italy) which draw together about 100 scientists from 13 countries who presented 66 contributions (the abstract volume can be downloaded from http://www.geoscienze.unipd.it/workshop/WorkshopAbstractVolume_cover.pdf). Many of the topics addressed during the workshop (e.g. rock friction) have implications for the understanding of other processes important in Earth Sciences such as landslides mechanics, the development of volcanic conduits and plug emplacement mechanics and overlap with other disciplines including material sciences and engineering (wear, milling, lubrication, etc.). Nineteen of these contributions are published in this Special Volume spanning from field to theoretical and experimental studies of interseismic and coseismic processes.

The field contributions begin with a study of deep-seated pseudotachylytes associated with high-temperature mylonites (White, 2012). The author speculates about the possible formation mechanisms of these pseudotachylytes which might be related to non-volcanic tremor recorded at the surface along some modern faults (Obara, 2002; Shelly, 2010). The work by Bestmann et al. (2012) documents the occurrence of crystal-plastic behaviour and ultrafine recrystallization of quartz in the host rock adjacent to pseudotachylyte-bearing faults exhumed from typical crustal hypocentral depths (9–11 km). The crystal-plastic deformation is constrained to have occurred during the short-lived high-temperature transient induced by frictional heating during coseismic slip and seems to be a characteristic of many pseudotachylyte-bearing faults. Such findings may be relevant in constraining the rheology of seismogenic faults. At shallower crustal levels, Oohashi et al. (2012) and Moore and Rymer (2012) address the role of frictionally weak minerals such as graphite (Atotsugawa Fault Zone, Japan) and saponite (San Andreas Fault, USA), respectively, in controlling fault weakening and creep in so-called large displacement mature fault zones.

Within the theoretical contributions, Noda and Shimamoto (2012) describe rock analogue experiments performed on salt that reproduce the pressure-dependent to pressure-insensitive transition by means of an empirically-based rate-and-state friction to flow law. This new constitutive law might find wide

(Beeler, 2006). The coseismic weakening and healing will be discussed in Fig. 2. b) Average earthquake energy budget for a fault per unit area (modified from Abercrombie and Rice, 2006; Kanamori and Rivera, 2006). This budget considers the whole fault and coseismic slip is averaged over the entire fault length. The total earthquake available energy per unit fault surface (area of AELO, Dahlen, 1977) includes the elastic strain energy and gravitational energy that will be released during the earthquake. The total energy is partitioned into radiated energy, fracture energy and frictional energy. The frictional energy (area below JHGEF) cannot be determined by seismic wave inversion analysis. The fracture energy (area of JABCKH) and radiated energy (area of DEGHK) can be determined by seismic wave inversion analysis. According to this energy partitioning, the area of ABC (the excess work done to achieve the yield strength due to an increase in stress prior to dynamic slip) and of EFG (energy exchanged during fault healing) is balanced by the area of CDK.

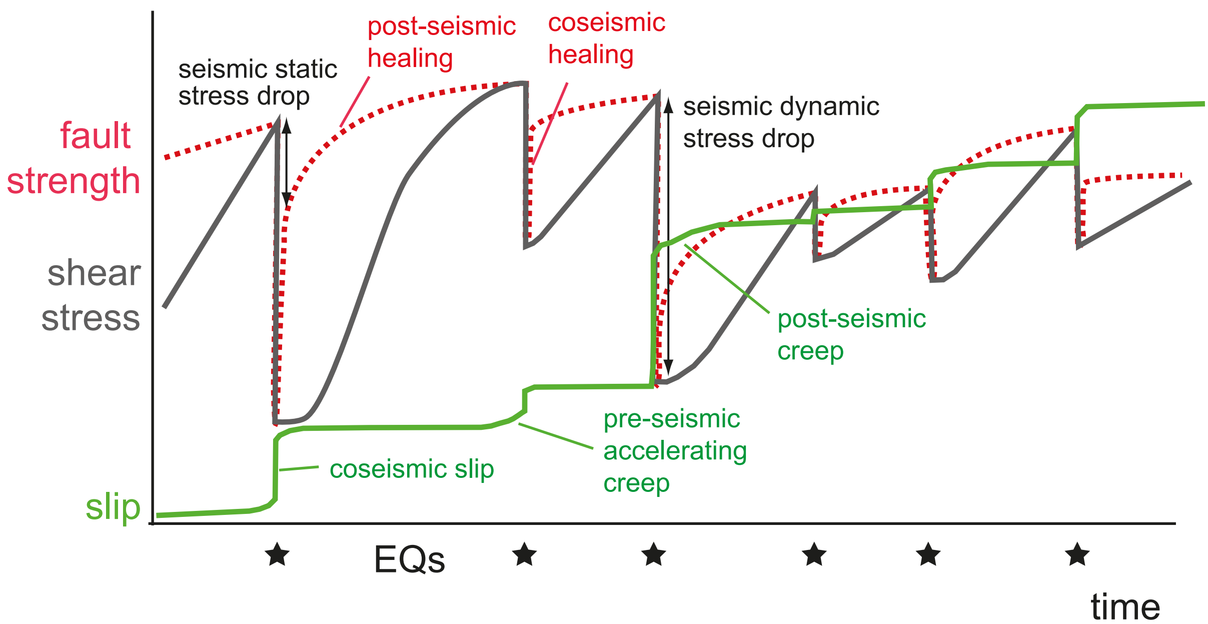

Fig. 2. The fault strength and shear stress on a fault patch evolve with time during the seismic cycle. Fault failure is the result of the complex feedback between the loading stress and the evolution of the fault strength with time. Pre-seismic accelerating creep might occur for some earthquakes. Post-seismic creep might be as large as coseismic slip in some fault patches. This framework renders a physically-based earthquake forecasting model an extremely challenging task.

application in seismic cycle modelling studies. The effects of permeability and porosity evolution with time on the hydraulic diffusivity in the seismic cycle are theoretically investigated by Bizzarri (2012), who explores numerically earthquake recurrence timescales due to porosity and permeability reduction with time around fault zones. The activation of coseismic weakening processes related to the physics of dense granular flows, which includes the elastic strain energy stored in the grains during loading and fragmentation and its release to sustain fault lubrication (Davies and McSaveney, 2012) or more conventional models which consider thermochemical pressurization due to the release of supercritical fluids by lattice breakdown induced by frictional heating (Veveakis et al., 2012) are also investigated theoretically here.

Most of these theoretical approaches suffer from a lack of experimental data to support the input parameters and assumptions: here the need is for dedicated experiments from the rock physics community. One of the most relevant unknown parameters is the coseismic fault zone permeability, as it should particularly control the pressurization of the slipping zone. Frictional heating by coseismic slip triggers thermal expansion of pore fluids and of the solid matrix. At the same time, the comminution of fault materials due to frictional sliding (see the discussion about grain comminution and sintering in Sawai et al., 2012; Togo and Shimamoto, 2012), breakdown of minerals which might release fluids (CO_2, H_2O, Han et al., 2007; Brantut et al., 2008; Hirono et al., 2007) and rock pulverization and fracturing at the rupture tip (Reches and Dewers, 2005) may dramatically change the pre-seismic and coseismic permeability conditions. Tanikawa et al. (2012) report 2012 the first attempt to determine fault zone transport properties under coseismic slip deformation conditions (slip rates of about 1 m/s). A highly relevant issue in experimentally-based studies is scaling, which can make the extrapolation of mechanical data to nature extremely challenging. This is addressed in the paper by Beeler et al. (2012) which shows that, at least for this experimental configuration (large sample size in a biaxial press), radiated energy is negligible compared to fracture energy and frictional work and that experimentally-determined values of seismic source parameters (static stress drops, fracture efficiency) are compatible with seismological observations. As previously discussed, seismic energy budgets cannot be determined by seismological investigations. This topic inspired the contributions by Togo and Shimamoto (2012), Sawai et al. (2012) and Hirose et al. (2012). By performing experiments with rotary shear apparatuses that reproduce seismic slip rate and displacements typical of seismic slip, both groups of authors confirm that the surface fracture energy remains a small fraction of the earthquake energy budget (mostly being heat that controls the friction evolution in the slipping zone). These papers first highlight the technical difficulties in measuring the grain-size distribution of ultrafine gouges (often nanometric in size), as discussed by Storti and Balsamo (2010). Then, even considering the fact that these experiments do not reproduce all the coseismic processes responsible for the formation of new fault surface (the large stress perturbations expected at the rupture tip are not reproduced with such experimental configuration), the grain surface measured after the experiments is probably affected by welding and sintering processes. Sintering, by decreasing the grain surface area during slipping zone cooling, renders the estimate of the energy budget from field and microstructural-based studies quite difficult. Hirose et al. (2012) focus on the characterization of wear process and the dependence of wear rate with slip rate. According to these new studies, in the case of silicate-rich crystalline rocks, the wear rate vs. displacement switches from the known power law at sub-seismic slip rates towards an exponential law at seismic slip rates (about 1 m/s). Since most of the displacement in crustal faults is probably accommodated by seismic slip, this relationship can and should in future be tested in exhumed fault zones. Pec et al. (2012) investigate the feedback between pressure-dependent and pressure-insensitive deformation processes in experiments performed on granitic gouges at elevated temperatures (300–500 °C) and confining pressures (500–1500 MPa). Not surprisingly, rocks deformed at higher temperature are weaker (initial peak friction decreases with increasing temperature and

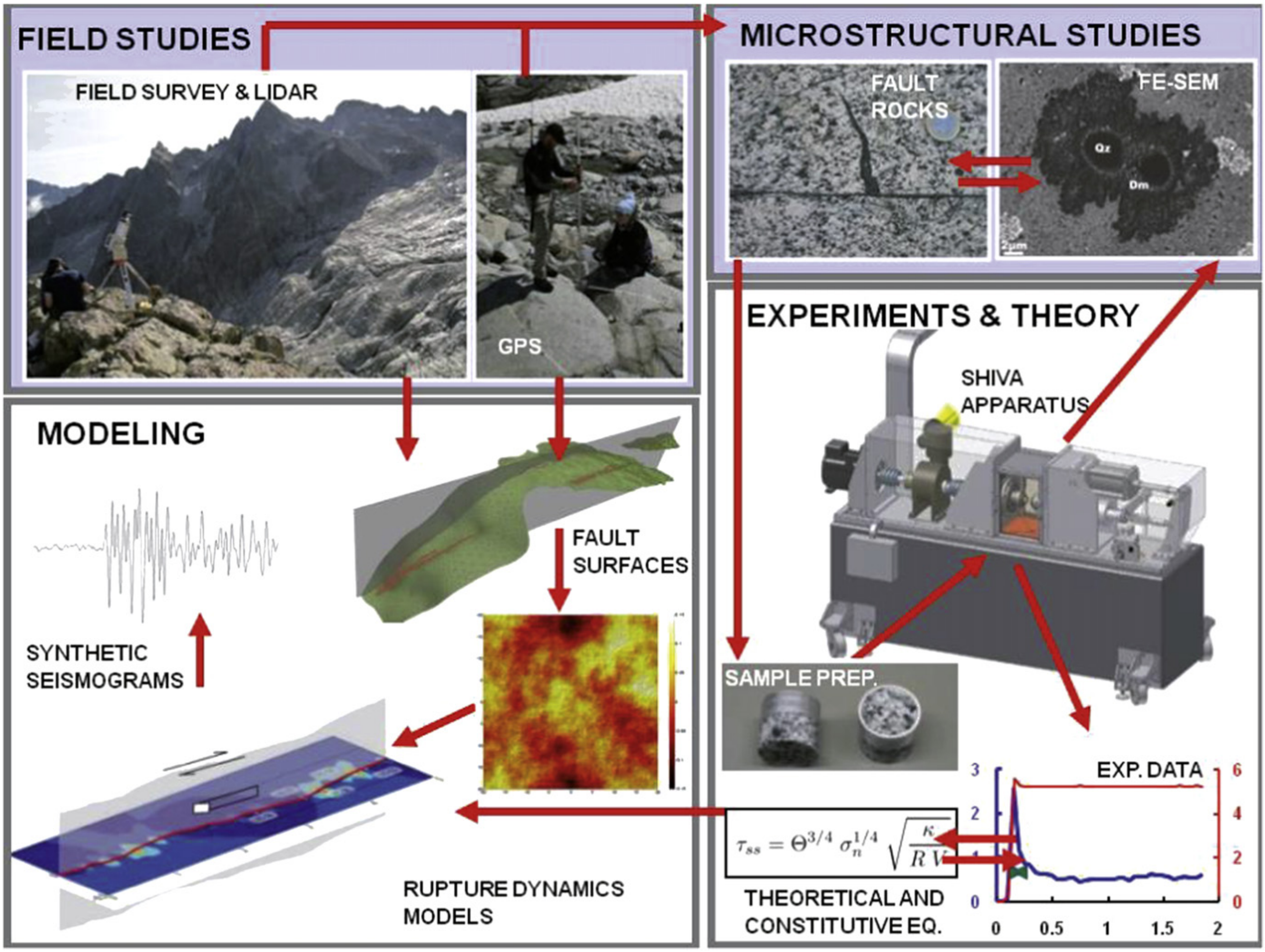

Fig. 3. A multidisciplinary and complementary approach to the orthodox "seismologically based" study of earthquake source physics highlighting the central role of Structural Geology. Quantitative field studies of exhumed faults, microstructural investigations and rock deformation experiments allow to us to better constrain the geometry of natural seismogenic fault zones, to identify processes occurring during faulting and to improve our understanding of the rheology of fault rock materials. Numerical modelling allows the synthesis of the above observations in a "geologically based" model of seismic faulting (see Di Toro et al., 2009 for discussion).

confining pressure,) but, remarkably, the formation of spectacular S-C′ fabrics is accompanied by chemical reactions and mass transfer even at the low temperatures investigated in the experiments. Given the textural similarity with natural fault products, these studies yield sound constraints concerning the rheological properties of the frictional-viscous transition and the amount of elastic strain energy, if any, that might be stored and eventually released in seismic ruptures.

The determination of the frictional properties of rocks in the laboratory remains of paramount importance. In fact, earthquake nucleation, coseismic rupture and slip, afterslip and creep, depend, on the evolution and dependence of friction with slip and slip rate (e.g. Dieterich, 1978; Scholz, 2002). In this volume, the determination of the friction coefficient in different rock materials is addressed in several studies by means of experiments that reproduce the *in situ* (temperature and pressure) frictional properties of megathrust smectite- and illite-rich fault gouges, including the transition from stable to unstable slip conditions that control the depth of the locked section in subduction-related megathrust environments (den Hartog et al., 2012). The frictional properties of saponite-bearing faults (also found at SAFOD, see Moore and Rymer, 2012; Holdsworth et al., 2011) are investigated by Sone et al. (2012) who show that they display an extremely low friction value (<0.12) and velocity strengthening behaviour. Such experimental observations support the "absolute" weakness *sensu* Rice (1992) and creeping behaviour of some segments of major fault zones. Experimental studies aim to discriminate both the frictional behaviour and also the physical processes responsible for dynamic weakening at seismic slip initiation. The study by Tisato et al. (2012) reveals that, whilst the achievement of a critical slip rate leads to a dramatic weakening in limestones compatible with the flash heating and weakening model proposed by Rice (2006), the physical model, at least for these experiments performed in limestones, does not seem consistent with the microstructural and mineralogical observations. The flash heating friction-law fails to fully account for the observed mechanical data.

Pseudotachylytes formed due to frictional melting in volcanic conduits have been recently discovered (Tuffen and Dingwell, 2005) and this Volume carries a study that attempts to introduce fault physico-chemical processes and methods into the study of the physics of volcanic conduits and acid spine emplacement (Kendrick et al., 2012). Though preliminary, the application of recent findings about physical properties of silicic magmas to the study of pseudotachylytes seems extremely promising. Melt lubrication here is controlled by several parameters: fault roughness, strain rate (i.e. melt thickness and slip rate), melt escaping distance, and, of course,

Fig. 4. Prof. Toshihiko Shimamoto during the party in his honour at the Workshop on *Physico-chemical processes in seismic faults* held on the 18th–20th November 2010 in Padua (Italy).

melt viscosity (Persson, 2000; Hirose and Shimamoto, 2005; Nielsen et al., 2008, 2010 for discussion). The latter depends on melt composition and temperature, but also on clast and vesicle content and shape of the clasts. The use of a Newtonian rheology might result in a lower bound estimate of the melt strength (Spray, 1993; Ujiie et al., 2007). The non-Newtonian rheology of experimentally-produced friction-induced melts is discussed in Lavallée et al. (2012). This contribution shows the potential of the interactions between Volcanology, Structural Geology and Experimental Rock Deformation, and how the knowledge gained from different disciplines can yield new views and understanding of volcanic and fault-related processes.

Last but not the least, the workshop in Padua was the occasion to celebrate the retirement of Prof. Toshihiko Shimamoto from the University of Hiroshima (Japan) (but not his retirement from research) and his contribution to the understanding of the physico-chemical processes during the seismic cycle (Fig. 4). Prof. Shimamoto's findings and his experimental methods have found broad applications in other fields (e.g. the mechanics of landslides, Ferri et al., 2011). This volume, with several contributions co-authored by him and his former students, gives a clear indication of the broad span of research topics he has covered in his career (from frictional properties to the pressure-dependent to pressure-independent transition, or to earthquake energy budgets: Noda and Shimamoto, 2012; Togo and Shimamoto, 2012; den Hartog et al., 2012; Sawai et al., 2012; Sone et al., 2012; Hirose et al., 2012; Oohashi et al., 2012).

Prof. Shimamoto has pioneered the linking of field studies to experimental (and in some cases numerical studies): he remains one of the few scientists who is able to design sophisticated experimental apparatuses and to conduct top quality field work. His many contributions of Prof. Shimamoto in earthquake physics include the following:

(1) The design of dedicated apparatus to investigate physical and transport properties of fault zones (permeameters, biaxial and triaxial apparatus) and rock frictional properties at seismic slip rates (high-velocity rotary shears) (Shimamoto and Tsutsumi, 1994; Kawamoto and Shimamoto, 1998; Noda and Shimamoto, 2010b; Wibberley and Shimamoto, 2003).
(2) The experimental investigation of the processes that lead the transition from frictional sliding to crystal-plastic flow (Shimamoto, 1986; Kawamoto and Shimamoto, 1998), the proposal of a rate-and-state flow law (Noda and Shimamoto, 2010b), and the development of a friction to flow law and fault stability analysis based on this law (Noda and Shimamoto, 2012).
(3) First determination of rock friction at seismic slip rates (Tsutsumi and Shimamoto, 1997), measurements of fault-zone permeability and thermal pressurization analysis (Wibberley and Shimamoto, 2003; 2005), experimental studies on frictional melting processes (Hirose and Shimamoto, 2005), first fault-gouge experiments at seismic slip rates (Mizoguchi et al., 2007), mineral decomposition and its effect on thermal pressurization (Han et al., 2007; Brantut et al., 2008), and high-velocity friction experiments on nano-particles and proposal of powder lubrication (Han et al., 2010). The experimental work lies at the foundation of several numerical or theoretical modelling studies of earthquake faulting (Fialko and Khazan, 2005; Sirono et al., 2006; Nielsen et al., 2008; Rice, 2006; Beeler et al., 2008) and of slow slip events (Shibazaki and Shimamoto, 2007).

But perhaps most importantly, it has been Prof. Shimamoto's enthusiasm and dedication that has inspired the work of many young (and may be now not-so-young) researchers that will be his most lasting legacy. It is therefore appropriate that this volume of papers should be dedicated to Toshi in recognition of his fundamental and long-lasting influence in this area of scientific endeavour.

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