Preface

The topic Avalanches in Functional Materials and Geophysics is a highly researched area of science with significant cross-fertilization between approaches in the two fields. Avalanches occur in many physical systems spanning microscopic to macroscopic length scales. Beyond the usual snow avalanches and seismic activity, acoustic emission measurements identify avalanches during phase transitions, the collapse of porous materials under pressure and many other materials related processes. One of the major objectives of the book is to identify common experimental characterization, theoretical and simulation techniques as well as statistical data analysis, and similar predictive modelling and phenomenology in materials science and geophysics. The book is likely to be broadly accessible and caters to beginning researchers, graduate students as well as experts.

The book contains a dozen chapters, which represent partly a review with a wide perspective and original research aimed at identifying open issues. The first two chapters invoke the statistical mechanics approach to earthquakes and an associated mean-field theory to study avalanches. A series of simple models of earthquake faults is investigated. The role of fault geometry, friction and noise in determining the statistics of earthquakes is explored. The statistics and the dynamics of slip avalanches in slowly deformed solids are reviewed. These results have implications for materials testing, failure prediction, and hazard prevention. The next three chapters address how to mimic earthquakes in a laboratory setting ("labquakes") in porous materials as well as geological aspects such as the role of various rock types in earthquakes. A review of recent acoustic emission experiments during the compression of synthetic porous materials under controlled force rates is presented. The statistical analysis of the recorded signals of laboratory experiments allows a comparison with the statistics of earthquakes from available seismic data. Different methods to characterize individual acoustic emission avalanches and their time correlations are discussed. The results indicate that the failure dynamics of materials can be studied by measuring strain drops under slow compression, opening the possibility to study earthquake dynamics in the laboratory at non-ambient conditions.

Similarly, in rock physics sudden changes in internal stress associated with microscopically brittle rupture events lead to acoustic emissions that can be recorded on the sample boundary, and used to infer the state of internal damage. Crackling noise is inherently stochastic, but the population of events often exhibits remarkably robust scaling properties, in terms of the source area, duration, energy, and in the waiting time between events. Despite the stationary strain rate and the lack of any time-dependent weakening processes, the results are all characterized by emergent power law distributions over a broad range of scales, in agreement with experimental observation. As deformation evolves, the scaling exponents change systematically in a way that is similar to the evolution of damage in experiments on real sedimentary rocks. The potential for real-time forecasting of catastrophic failure obeying such scaling rules is then examined by using synthetic and real data tests, e.g. prior to volcanic eruptions.

Chapters 6–9 deal with avalanches in structural phase transitions, particularly in martensites, and more generally both the experimental and the simulation studies of pinning and avalanches in ferroelastics—materials in which strain serves as the order parameter for phase transitions. Solids subject to continuous changes of temperature or mechanical load often exhibit discontinuous avalanche-like responses, e.g. avalanche dynamics have been observed during plastic deformation, fracture, domain switching in ferroic materials or martensitic transformations. The statistical analysis of avalanches reveals a very complex scenario with a distinctive lack of characteristic scales. Efforts to understand the characteristics of avalanches in martensites through mathematical modelling are reviewed. Analogously, nano-scale multiferroics often display sudden, jerky domain movements under weak external fields. These domain movements include retracting twin domains, kinks in domain walls, jamming between walls and changes in complex tweed patterns. It is shown that the probability density function of the jerk distribution follows power law statistics at sufficiently low temperatures and thermally activated jumps at high temperatures, which explains the mixing of thermal and athermal events during acoustic emission.

Time-lapse optical microscopy of certain ferroelastic single crystals allows the propagation and retraction of individual needle domains to be observed under conditions of slowly varying shear stress. Optical observation and thermodynamic analysis show that the continuous behaviour is thermally activated. The avalanches follow power law behaviour in agreement with self-similar avalanches close to the depinning threshold. Singularities of the characteristic (Larkin) length occur when the front line breaks. Three physical systems are discussed in which the distributions of certain variables are centred around a most probable value. Each microstructural-related event proceeds through a multitude of smaller mesoscopic events that span several orders of magnitude. Statistical analyses of other variables, associated with the mesoscopic events, follow a scale-invariant power law distribution. The origins for the co-existence of events at different scales and their different statistical distributions are discussed for the physical characteristics of the explored systems.

Chapter 10 studies avalanches in metallic glasses whereas Chap. 11 deals with yield and irreversibility in amorphous solids. The atomistic mechanism of deformation in metallic liquids and glasses is discussed in view of the local topology of atomic connectivity. In crystals the topology of atomic connectivity network is fixed, and deviation from it defines lattice defects. In liquids and glasses, however, the topology is open and flexible, and fluctuates in time and space. Collective phenomena, including shear-transformation-zones and their avalanche, govern the macroscopic deformation in supercooled liquids and glasses. The description of the structure and dynamics of liquids and glasses through local topology is likely to advance the field. Similarly, a fundamental problem in the physics of amorphous materials is understanding the transition from reversible to irreversible plastic behaviour and its connection to the concept of yield. Under periodic shear, amorphous solids undergo a transition from deterministic, periodic behaviour to chaotic, diffusive behaviour as a function of strain. It has been related to a depinning-like transition in which cooperative avalanche events span the system. An overview of recent work focused on the nature of yield in amorphous systems from a cooperative and dynamical point of view is presented.

Finally, Chap. 12 describes avalanches in the context of fluid imbibition. In particular, the invasion of an open fracture by a viscous wetting fluid is reviewed in the context of research on the spatiotemporal dynamics of fronts in disordered media. Competition of forces at different length scales leads to an initially flat front undergoing a kinetic roughening process, leading to a statistically stationary state characterized by critical interfacial fluctuations and a collective avalanche dynamics. A scale-dependent statistical analysis of the temporal behaviour of the spatially averaged velocity of the front reveals the presence of non-Gaussian fluctuations, strongly intermittent dynamics and global avalanches.

These 12 chapters discuss a multitude of open questions and set the stage for future research in this highly multidisciplinary field. They also provide a much needed integration between two broad subject areas, materials and geophysics, which is expected to usher into further insights and a better understanding of avalanches. However, much remains to be improved such as the detailed analysis of avalanche processes. Besides seasoned researchers the book will also serve as a valuable resource for graduate students in materials science and engineering, condensed matter physics, geophysics and other related disciplines.

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