1 Motivation: Earthquake science challenges

Our purpose is to analyze the causes of recent failures in earthquake forecasting, as well as the difficulties of earthquake investigation. It is widely accepted that failure has dogged the extensive efforts of the last 30 years to find "reliable" earthquake prediction methods, the efforts which culminated in the Parkfield prediction experiment (Roeloffs and Langbein 1994; Bakun *et al.* 2005 and their references) in the USA and the Tokai experiment in Japan (Mogi 1995). Lomnitz (1994), Evans (1997), Geller *et al.* (1997), Jordan (1997), Scholz (1997), Snieder and van Eck (1997), and Hough (2009) discuss various aspects of earthquake prediction and its lack of success. Jordan (1997) comments that

> *The collapse of earthquake prediction as a unifying theme and driving force behind earthquake science has caused a deep crisis.*

Why does theoretical physics fail to explain and predict earthquake occurrence? The difficulties of seismic analysis are obvious. Earthquake processes are inherently multidimensional (Kagan and Vere-Jones 1996; Kagan 2006): in addition to the origin time, 3-D locations, and measures of size for each earthquake, the orientation of the rupture surface and its displacement requires for its representation either second-rank tensors or quaternions (see more below). Earthquake occurrence is characterized by extreme randomness; the stochastic nature of seismicity is not reducible by more numerous or more accurate measurements. Even a cursory inspection of seismological datasets suggests that earthquake occurrence as well as earthquake fault geometry are scale-invariant or fractal (Mandelbrot 1983; Kagan and Vere-Jones 1996; Turcotte 1997; Sornette 2003; Kagan 2006; Sornette and Werner 2008). This means that the statistical distributions that control earthquake occurrence are power-law or stable (Lévy-stable) distributions. See also http://www.esi-topics.com/earthquakes/interviews/YanYKagan.html.

After looking at recent publications on earthquake physics (for example, Kostrov and Das 1988; Lee *et al.* 2002; Scholz 2002; Kanamori and Brodsky 2004; Ben-Zion 2008), one gets the impression that knowledge of earthquake

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process is still at a rudimentary level. Why has progress in understanding earthquakes been so slow? Kagan (1992a) compared the seismicity description to another major problem in theoretical physics: turbulence of fluids. Both phenomena are characterized by multidimensionality and stochasticity. Their major statistical ingredients are scale-invariant, and both have hierarchically organized structures. Moreover, the scale of self-similar structures in seismicity and turbulence extends over many orders of magnitude. The size of major structures which control deformation patterns in turbulence and brittle fracture is comparable to the maximum size of the region (see more in Kagan 2006).

Yaglom (2001, p. 4) commented that turbulence status differs from many other complex problems which twentieth-century physics has solved or has considered.

> *[These problems] deal with some very special and complicated objects and processes relating to some extreme conditions which are very far from realities of the ordinary life … However, turbulence theory deals with the most ordinary and simple realities of the everyday life such as, e.g., the jet of water spurting from the kitchen tap. Therefore, the turbulence is well-deservedly often called "the last great unsolved problem of the classical physics."*

Although solving the Navier-Stokes equations, describing turbulent motion in fluids is one of the seven millennium mathematical problems for the twenty-first century (see http://www.claymath.org/millennium/), the turbulence problem is not among the ten millennium problems in physics presented by the University of Michigan, Ann Arbor (see http://feynman.physics.lsa.umich.edu/-strings2000/millennium.html), or among the 11 problems by the National Research Council's board on physics and astronomy (Haseltine 2002). In his extensive and wide-ranging review of current theoretical physics, Penrose (2005) does not include the turbulence or Navier-Stokes equations in the book index.

Like fluid turbulence, the brittle fracture of solids is commonly encountered in everyday life, but so far there is no real theory explaining its properties or predicting outcomes of the simplest occurrences, such as a glass breaking. Although computer simulations of brittle fracture (for example, see O'Brien and Hodgins 1999) are becoming more realistic, they cannot yet provide a scientifically faithful representation. Brittle fracture is a more difficult scientific problem than turbulence, and while the latter has attracted first-class mathematicians and physicists, no such interest has been shown in the mathematical theory of fracture and large-scale deformation of solids.

In this book we first consider multidimensional stochastic models approximating earthquake occurrence. Then we apply modern statistical methods to investigate distributions of earthquake numbers, size, time, space, and focal mechanisms. Statistical analysis of earthquake catalogs based on stochastic point process theory provides the groundwork for long- and short-term forecasts. These forecasts are rigorously tested against future seismicity records. Therefore, here statistical study of earthquake occurrence results in verifiable earthquake prediction.

The book has 12 chapters. In this chapter, we discuss the fundamental challenges which face earthquake science. In Chapter 2 we review the seismological background information necessary for further discussion as well as basic models of earthquake occurrence. Chapter 3 describes several multidimensional stochastic models used to approximate earthquake occurrence. They are all based on the theory of branching processes; the multidimensional structure of earthquake occurrence is modeled. Chapter 4 discusses the distribution of earthquake numbers in various temporal-spatial windows. In Chapters 5–8 some evidence for the scale-invariance of earthquake process is presented, in particular, one-dimensional marginal distributions for the multidimensional earthquake process are considered. Fractal distributions of earthquake size, time intervals, spatial patterns, focal mechanism, and stress are discussed. Chapter 9 describes the application of stochastic point processes for statistical analysis of earthquake catalogs and summarizes the results of such analysis. Chapter 10 describes the application of the results of Chapter 9 for long- and short-term prediction of an earthquake occurrence. Methods of quantitative testing of earthquake forecasts, and measuring their effectiveness or skill are discussed in Chapter 11. The final discussion (Chapter 12) summarizes the results obtained thus far and presents problems and challenges still facing seismologists and statisticians.