# Working Group Sessions: issues and questions

Major session issues and questions identified by workshop convenors prior to the workshop are listed below. Summaries preceeding the papers presented in each session review outcomes and discussions.

## Session 1.1: Modelling the micro physics underlying earthquake nucleation processes and rupture

Convenors: D. Place and Y. Bai

Modelling microscopic properties of rock allows non-linear and complex macroscopic behaviour to be simulated. Rather than specifying a "true" representation of rock at a microscopic scale, models use empirical properties at a mesoscopic scale such that the correct macroscopic behaviour is simulated. The objectives of Session 1.1 are:

(1) to explore properties than can be modelled at the grain scale and to explore macroscopic behaviour that can be reproduced by such models, and

(2) to gain insight from micro/meso-scopic characteristics to predict macroscopic failure.

### *1. Modelling rock grain interactions*

Different properties can be modelled at a grain-scale such as elasticity, roughness friction, thermal effects and phase transitions. However, emergent properties of a model can be used to specify material properties. For instance rather than specifying a roughness at the grain scale, an assembly of smaller grains can be used.

- What are the properties that need to be modelled at the grain scale?
- What properties can be simulated without excessive computational cost?
- What is the impact on the macroscopic behaviour of not modelling a given grain-scale property?

## *2. Modelling rupture processes*

In the process of fracture, grains of rocks can break down until a lower scale is reached. This may be of order microns to the scale of molecules. Cracks and complex structures are present at many scales. The disorder present at the microscopic scale can be significant at a larger scale.

- How can the evolution of micro-damage such as micro-cracks be used to predict macroscopic failure?
- What intrinsic factors in solids govern macroscopic failure?

## Session 1.2: Frictional behaviour of rocks, gouge layers and complex fault zones: simulation, observation and scaling

Convenors: M. Blanpied, P. Mora and M. Ohnaka

Earthquakes result from the formation of and/or rapid sliding of faults. Decades of laboratory, field, and theoretical work has shown fault slip to be enormously complicated, due to the wide variety of rock types, physical and chemical environments, deformation rates, and deformation mechanisms at play. The objectives of Session 1.2 are to identify what micro-scale elements of the faulting and fault slip processes are the critical ones in determining macroscopic faulting behavior, and to discuss conceptual strategies for incorporating these key processes into tractable models. This session focusses on model philosophy and leaves the "nuts and bolts" of numerical design to Session 1.1. Three main topics are explored:

### 1. *Identifying the key deformation processes*

- What are the key deformation processes and conditions that must be taken into account when constructing a reasonably representative micro-scale fault model?

### 2. *Scaling issues and constitutive laws*

- How has the complexity of nature been boiled down into useful mathematical laws?
- Are these laws useful building blocks for micro-scale model development, or useful benchmarks to judge their success?
- How is it possible using simulations to go from laboratory to fault zone scale to access fault zone behavior?

### 3. *Model-building strategies*

- How best can key issues of scaling and process be incorporated into numerical models?
- Do such models need to simulate the full earthquake cycle or only a portion of it (e.g. just the quasi-static or just the fully dynamic portions)?
- Can a single type of model hope to cover conditions from near surface to sub-seismogenic zone?
- What trade-offs of realism for tractability are permissible?

## Session 2.1: Physical modelling and simulation of the earthquake cycle

**Convenors:** M. Matsu'ura, D. Turcotte and K. Wang

The ultimate scientific goal of ACES is to develop a realistic unified simulation model for the complete earthquake generation process and cycles in the Asia-Pacific region, which consists of regional models in each of the different tectonic settings; transform plate boundaries, subduction zones, and intraplate regions. Macroscopic Working Group (WG2) directly contributes to the achievement of this goal. The entire process of earthquake generation consists of tectonic loading due to relative plate motion, quasi-static rupture nucleation, dynamic rupture propagation and stop, and fault lithification and healing. Propagation of dynamic rupture and seismic waves and interaction of complex fault systems will be discussed in the closely related Sessions, 2.2 and 2.3, of WG2. Therefore, in Session 2.1, we will focus on the macroscopic modelling of earthquake cycles based on continuum mechanics and tectonic environments for earthquake generation. The key scientific issues pertinent to this session are as follows.

### *1. Macroscopic modelling of earthquake cycles and predictability of earthquakes*

So far many macroscopic models of earthquake cycles have been proposed.

- Is the concept of earthquake cycles reasonable?
- Can large earthquakes be separated from smaller earthquakes?
- How should we describe the basic equations governing the earthquake generation cycle?

### *2. Crustal structure and tectonic environments for earthquake generation*

The processes of earthquake generation strongly depend on fault geometry, frictional properties, and tectonic environments.

- What are the key parameters controlling the earthquake generation processes?

### *3. Physical process of tectonic stress accumulation and release during earthquake cycles*

From a macroscopic point of view, the earthquake generation cycle can be regarded as the process of tectonic stress accumulation and release. How can we model this process reasonably?

## Session 2.2: Simulation of earthquake rupture, seismic wave propagation and strong motion

Convenors: R. Madariaga, E. Fukuyama and R. Archuleta

This session aims to review the current status of what can be achieved in:

- ***Detailed earthquake rupture modeling***
- ***Detailed nearfield ground motion***

Key questions to be addressed are:

- With what degree of realism can single earthquake ruptures be modelled?
- What is the resolution of kinematic inversions of fault parameters from seismic observations and what are the problems of modelling fault at these resolutions?
- What "friction law" should be used?
- How well do the different numerical methods (finite differences, finite elements or boundary integral equations) model rupture phenomena?
- What are the conditions for complexity of rupture phenomena?

## Session 2.3: Simulation and observations of complex interacting fault systems

Convenors: S. Jaumé and J. Rundle

Earthquakes do not occur in isolation from one another, but they and the faults upon which they occur form a complex web of interacting elements. The objective of Session 2.3 is to explore the means by which earthquakes and faults interact and how this affects the dynamics of earthquake occurrence and the resulting space-time patterns of seismicity. We will explore three main topics during this session:

### *1. Long/short range interactions versus long/short range correlations in interacting fault systems*

Many simulation models of the earthquake process show highly complex behavior even though they include only nearest-neighbor interactions among the model elements. However, observations of earthquake triggering suggest interactions at distances far greater than an earthquake rupture length. Are long range interactions necessary to model the earthquake process, or can the observed long-range correlations be modelled with only short-range interactions?

### *2. Application of frictional relationships to stress transfer and dynamic triggering*

Early attempts to model earthquake and fault interactions assumed a simple Coulomb failure criteria for stress transfer. However, laboratory derived frictional relationships show that the failure strength on fault surfaces can be highly dependent upon their loading history. This topic will explore the application of these frictional relationships to the triggering/shadowing of future earthquake occurrence.

### *3. Dependence of spatio-temporal seismicity patterns upon the structure of interacting fault systems*

Natural fault systems show a high degree of heterogeneity in their structure, ranging from fairly simple systems with only one or a few active faults to complex regions with many active faults of different orientation and sense of slip. Active faults also come in a hierarchy of different sizes.

- How does this complexity affect the dynamics of regional scale fault interaction?

## Session 3.1: Macroscopic methods (FEM, FD, PS, SE) of earthquake faulting and waves

Convenors: K. Hirahara and D. Komatitsch

Numerical simulation of earthquake faulting and wave propagation in realistic media, that include laterally heterogeneous elastic and viscoelastic complexity with several scales, requires highly sophisticated numerical techniques. The objective of Session 3.1 is to study computational methods and algorithms for the simulation models, common tools and routines for their implementation on super-parallel computer systems for large-scale problems, efficient methods for mesh design in 3D for real structures, and visualization and evaluation strategy of simulation results. We examine the present status of this subject and discuss future directions. In this session, we would like to explore the following three issues:

### *1. Towards large-scale computing*

For large-scale problems with typically 100 million degrees of freedom or more, special simulation techniques are required, especially when using parallel computers. These new techniques will be discussed and analyzed.

### *2. Towards more realistic simulation of earthquake cycle and earthquake faulting*

We will discuss technical problems related to the quasi-static simulation of the earthquake cycle on plate interfaces and inland faults due to relative plate motions, which are in particular the introduction and correct representation of the fault interface, the allowance of a large amount of slip on the interface, the implementation of friction laws, anelastic properties, and so on. Problems related to dynamic simulation of earthquake faulting will also be examined.

### *3. Towards realistic simulation of wave propagation in large-scale complex media*

As observed for instance during the 1995 Kobe earthquake, abnormally strong ground motion, which is caused by the interaction of complex surface structure and waves emitted from the propagating rupture of earthquake faulting, causes great disaster. We will discuss technical problems related to realistic simulation of wave propagation in such basin structures, as well as in faulting regions.

## Session 3.2: Particle-based methods (LS, Distinct Element, MD) to simulate fault microphysics

Convenors: D. Place and H. Sakaguchi

Particle-based models often require a large number of particles. Particles are interacting together which requires enormous computation. Parallel computers provide the means to perform these calculations. However, because of the large number of particles, special algorithms are necessary to efficiently perform such simulations. The goals of Session 3.2 are:

(1) to expose the computational problems which arise from particle based methods such as the construction of particle assemblies ensuring localisation of nearest neighbour interactions, and

(2) to discuss solutions to these computational problems and how can they be implemented on a parallel computer.

This session is linked with Session 1.1. It aims to propose computational methods and algorithms to solve problems addressed in Session 1.1.

## Session 4.1: Inversion and assimilation of geodetic data

Convenors: T. Sagiya and B. Minster

In Session 4.1, we will discuss how to incorporate various observations into numerical simulations. Following are the main themes to be discussed.

### *1. Data assimilation technique used in earthquake simulations*

- In order to conduct realistic simulations, we definitely need to incorporate observations into numerical models. Data assimilation is therefore an indispensable part connecting observation and numerical models. The procedure includes updating observables in numerical models, providing constraints on the models, and revising the models themselves. Various kinds of analysis techniques, such as geophysical inversion, simulated annealing, and genetic algorithms, may be used in data assimilation. We will discuss these methods and try to formulate a general framework for the overall problem to be solved. In addition, to improve the ability of simulation models to forecast future crustal activities, data assimilation must be conducted in real time. We will discuss what we can learn from meteorology and oceanography in terms of real time data assimilation.

### *2. Combination of geodetic observations*

- Nowadays various types of geodetic observation are available such as GPS, InSAR, VLBI, SLR, borehole strainmeter, creep meter, etc. Sometimes we also need to incorporate traditional geodetic data that are sparsely sampled in time and perhaps of lesser quality, because these data span a long time period and include precious records of rare seismic events. Each type of observation offers its own advantages so that efficient and optimal combinations of these data are desirable. We will discuss what types of data are necessary in earthquake simulation and how we can combine them.

### *3. Application of inversion techniques in earthquake simulations*

- Inversion techniques are important tools to incorporate various observations into numerical models. Among various inversion techniques, geodetic inversion has a special significance because we have an explicit representation theorem between deformation of the earth and earthquake sources based on dislocation theory. We will discuss usage as well as limitations of inversion techniques in relation to earthquake simulations. We also discuss technical and theoretical development required for the earthquake simulations.

### ***4. Database system for earthquake simulations***

- In order to conduct data assimilation in an efficient way, it is essential to have a well-designed database system. Database systems are expected to contain all the information about earth structure, various types of observations, parameters controlling fault friction and failure laws, and so on. In order to be effective, databases should be designed so as to guarantee quick and efficient response to various queries. We will also discuss how to deal with incoming observation data in real time.

## Session 4.2: Physical scale dependencies, observed scaling relations and simulation

Convenors: M. Ohnaka and B. Shaw

We are primarily concerned with physical modeling/simulation of a large earthquake and eventual modeling for earthquake prediction, for which scale dependency of earthquake rupture is of critical importance. It is widely recognized that the size of an earthquake and some physical quantities inherent in the rupture are scale-dependent. Earlier studies show that these scale dependencies are closely related to geometric/structural properties of the seismogenic layer and the fault zone. Since the scale dependency is a key to quantitative modeling/simulation of the earthquake generation process, this is a crucial issue. Session 4.2 will address the following questions:

### *1. How are scale-dependent physical quantities scaled in terms of the underlying physics?*

Understanding of how the earthquake rupture that proceeds in a tectonic setting is scaled in terms of the underlying physics is a key to quantitative modeling/simulation of the earthquake generation process. Hence, how scale-dependent physical quantities are scaled in terms of the underlying physics will be explored.

### *2. How are earthquakes prescribed by geometric/structural properties of the seismogenic zone and the fault zone?*

The seismogenic layer and the fault zone include characteristic lengths of various scales departed from the self-similarity. The depth of seismogenic layer, fault segment size, fault zone thickness, barrier or asperity size will be representative examples of such characteristic scales. How the size of an earthquake is virtually prescribed by these characteristic scales in a given tectonic setting will be explored.

### *3. How are large earthquakes distinguished from small earthquakes?*

A large earthquake occurs along a preexisting fault of large-scale. An inhomogeneous fault evolves gradually with the repetition of earthquake slip on the fault in a given tectonic setting, and this will make a mature fault depart from the self-similarity. A large earthquake tends to occur along such a matured, large-scale fault. In addition, a large earthquake can take place, only after a large amount of the elastic strain energy has been stored in the medium surrounding the fault. Unless a sufficient amount of the strain energy has been stored in the medium surrounding a fault, a large earthquake cannot be induced along the fault by stress transfer due to fault-fault interaction. Once a large earthquake occurs, a long time period will be needed for the amount of strain energy to once again reach a critical level which has a potential to produce the next large earthquake on the same fault. This is contrasted with the case for a small earthquake, because the critical level or amount of the strain energy needed for a small earthquake to occur may be reached instantly by dynamic stress transfer. These factors suggest that large earthquakes may be distinguished from small earthquakes. This will be explored.

## Two additional questions will also be posed:

***4. What are the central observations a realistic model would have to match?***

***5. What is the relative importance of fixed heterogeneities, like material and geometrical ones, versus dynamic heterogeneities like stress? How do they interact?***

## Session 5.1: General session for earthquake forecasting and hazard quantification

**Convenors:** D. Jackson, X.C. Yin and Akio Yoshida

An important goal for earthquake studies is to predict observable features of the "earthquake system", that is the interacting material properties and state variables that cause earthquakes and are affected by earthquakes. Accurate and specific predictions of individual large earthquakes may be impossible in the foreseeable future (a much debated proposition), but there are many other types of prediction, in the broader sense, that would have practical benefits and would help to advance our understanding of earthquake science. Such "predictions" include probabilistic forecasts of future earthquake activity, predictions of displacements on specific faults or fault groups, predictions of ground motion that would result from hypothetical future earthquakes, and predictions that geophysical phenomena such as accelerated deformation or variations in seismicity should presage large earthquakes. The session will address questions related to the predictability of features of the earthquake system and the use of computer models to aid in constructing and testing such predictions, and the expectations that can rightly be placed on earthquake analogs such as laboratory and computer models.