Summary of Session 2:

Scaling physics and emergent behaviour at the micro and macro-scale: theory, simulation and observation

W. Klein(1) , M. Ohnaka(2), D. Sornette(3) and M.F. Xia(4)

(1) Professor William Klein, Physics Department, Boston University, 590 Commonwealth Avenue, Boston MA 02215 USA (e-mail: klein@buphyc.bu.edu; phone: +1 617-353-2188). (2) Professor Mitiyasu Ohnaka, Earthquake Research Institute, University of Tokyo, Yayoi 1-1-1, Bunkyo-ku, Tokyo 113-0032, JAPAN (e-mail ohnaka-m@eri.u-tokyo.ac.jp; phone: +81-3-3812-2111 (ext. 5711). (3) Professor Didier Sornette, Laboratoire de Physique de la Matiére Condensé, CNRS UMR6622 and Université des Sciences, B.P. 70, Parc Valrose, 06108, Nice Cedex 2, France (e-mail sornette@naxos.unice.fr; phone: +33-4-92-07-67-83). (4) Professor Mengfen Xia, Department of Physics, Peking University, Beijing 100871, P.R. CHINA. (e-mail: xiam@lnm.imech.ac.cn; phone: +86-10-6254-8133).

Observations of earthquake faults systems indicate strongly that these systems exhibit scaling and emergent behaviour. This behaviour is exhibited over extremely large intervals of space and time and it presents both a challenge and opportunity to geophysics to both explain the origin of this scaling and to use it to unify behaviour at several scales. The presentations in this session addressed both aspects of this scaling phenomenon. The methods used ranged from phenomenological scaling hypothesis to modelling to theoretical analysis.

One of the recurring questions that have arisen in the attempt to understand scaling is whether all earthquakes are generated by the same mechanism. In a presentation by Professor Aki (co-authored by Professor Jin) a model is presented which divides the fault plane into regions separated by barriers. In these regions sub-events are characterised by a slip weakening friction law. Observational data is used to estimate the size of these regions as well as to estimate the size of the nucleation zone. A systematic relation was also found between the magnitude and size of sub-events distributed over the fault plane called barrier intervals. The size of the barrier intervals decreases systematically with decreasing magnitude and will intersect the cohesive or nucleation zone size at a magnitude near 5 for major earthquakes in California. This indicates a cross over in behaviour from large to small earthquakes at magnitude 5.

In a talk presented by Professor Klein, co-authored by Professor Rundle as well as M. Anghol, G. Sá Martins and C. Ferguson, it was also suggested that there is a difference between large and small earthquakes. This distinction was based on the concept of a pseudo-spinodal, which is a critical like point, which exists for complex values of the physical parameters that determine the model. A characteristic length scale is related to the imaginary part of these complex numbers and this length scale is the dividing line between small events that can be described by equilibrium theories and large events that must be treated dynamically. This idea relies on the fact that the stress transfer is long, but not infinite in range, but is independent of fault structure.

As was pointed out in a presentation by Dr J. Dieterich, the non-planar nature of faults has important consequences for stress distribution and hence the distribution of both foreshocks and aftershocks. This highlights the question that was posed by the first two presentations summarized above. Namely: what is the role of fault structure and inherent correlations in generating the earthquake phenomenology? A related question that arises from these presentations is: are there levels of events for which geometry can be ignored and levels for which it cannot? A first step towards a solution of this problem was presented in a poster by D. Weatherley, which was co-authored by M.F. Xia and P. Mora. Weatherley reported on simulations of a cellular automaton with long-range stress transfer and a fractal distribution of stress failure thresholds. The weaker regions of the model corresponded to regions of heterogeneous stress distributions while areas with stronger failure thresholds had smoother stress distributions. This in turn correlated with larger earthquakes occurring in the smoother stress regions. This version of a cellular automaton also exhibited switching between a Gutenburg-Richter behaviour and a more characteristic behaviour for a moderate range stress transfer while short-range gave only Gutenburg-Richter behaviour and long-range gave characteristic events.

In another approach to testing whether there might be critical phenomena like behaviour associated with the onset of catastrophic earthquake events, Professor Xia presented the results of a study of critical sensitivity in a coupled pattern-mapping model. The paper was co-authored by Y. Wei, F. Ke and Y. Bai. It describes the effect of damage fraction p on a sensitivity ratio S. The sensitivity ratio is the ratio of the derivation of the released energy with respect to the stress at two values of the stress that differ by a small amount as_c where s_c is the average stress threshold and a is a small parameter. Identifying a critical value of the damage p_c with the point that indicates a large increase in the rate of energy release Xia et al show that approaching this point also generates a large increase in the fluctuation in S. A second sensitivity S* defined as the ratio of energy released with and without stochastic damage Dn divided by Dn shows very similar behaviour. These increased fluctuations are precursors to a catastrophic failure in the model. One possible interpretation is that this is a pseudo-spinodal as found in the model studied by Klein et al.

In a paper presented by Professor Knopoff and co-authored by Professor Yun-Tai the authors describe the physics of the seismic cycle of a single earthquake fault. This is done in terms of the dynamics of fracture and its effect on the material in its neighbourhood. The authors argue that in order for strong earthquakes to develop sharp onsets and obey physical constraints on the weakening of stress as a function of slip velocity, that the medium adjacent to the fault cannot be linear in the sense of elasticity. This allows for shockwaves to develop due to the large loading rate at the crack tip which shatters adjacent material. This shattered material is then the source of the aftershocks. They also argue that the development of a highly fractured zone across the main fault rupture is a zone of loss of fracture energy. This implies that granular collisions and rotations as well as fracturing must be considered along with sliding friction and elastic wave radiation in our understanding of dissipative processes. The authors then argue that the only way to introduce dissipation in these systems of large motions is to allow both slip and rotation simultaneously.

In a paper presented by H.B. Mühlhaus and coauthored by B.E. Hobbs, L. Moresi and H. Sakaguchi the subject of pressure dissolution fuelled mass transport during inhomogeneous deformation. Particular attention is paid to the buckling-type deformations. The authors examine the influence of the migration of chemical constituents on the evolution of fold geometry. Linear stability analysis of a set of derived dynamical and constitutive equations appears to give a good understanding of the modes of deformation at the onset of the deformation instability. Numerical solutions of these equations verify the picture presented by the instability analysis.

In a presentation (poster) by M.O. Petersen, C.H. Crumer and A.D. Frankel, probabilisitic seismic hazard assessment is presented for the Cascadia subduction zone in the Pacific Northwest of the United States. In particular, analysis is made of the uncertainty inherent in the hazard assessment. This uncertainty is caused by inherent uncertainty in the measurement of the parameters used to assess the hazard. Using Monte Carlo simulation a logic tree that represents the possible outcomes of hazard using different source or ground shaking models is sampled. Each branch of the tree represents a parameter that is needed in the hazard analysis. The uncertainty is specified as a coefficient of variation, the standard deviation divided by the mean.

In a poster presented by P.G. Somerville, observational constraints on the scaling of earthquake source parameters are presented. The author points out that recent observations of large earthquakes in Turkey and Taiwan confirm that the near fault seismic energy pulse is in a narrow band whose period increases with magnitude. Recent earthquakes also have weak ground motions at short and intermediate periods (0.1 to 3.0 seconds). These are surprisingly weaker than those at smaller magnitude events. These observations, the author argues require re-evaluation of the magnitude scaling in current models of near fault ground motions.

A presentation by Professor Ohnaka investigates the role of physical scale in unifying slip and fracture laboratory data with ruptures on faults. The author argues that a unification of data on these widely divergent scales can be obtained if the geometric irregularity of the rupturing surfaces is properly incorporated into the analysis. The author argues that the existence of patches with the shear fracture strength of initially intact rock is a key element in generating large earthquakes. Therefore if there is a constitutive law that governs earthquake structure, the law should be formulated as a unifying constitutive law that governs both frictional slip failure and shear fracture of intact rock. The author also argues that the key component that describes the material roughness which must be incorporated into the scaling is the characteristic length associated with the deviation from fractality for a given fractal band. Using this idea the author argues that laboratory scale and fault scale data can be presented as parts of a unified picture.

In a paper presented by Professor J. Rundle and co-authored by A. Donnellan, G. Fox, W. Klein, P. Rundle and K. Tiampo, an overview is presented of research into the construction and implementation of General Earthquake Models. The author describes the results of the simulation of a model of a geometrically complex network of horizontally slipping strike slip faults existing in southern California. The main results are that 1) The network dynamics is very different from what is found on single isolated faults due to elastic inhibiting interactions not present on single faults and 2) The stress dissipation properties of the fault friction law plays an important role in determining the dynamics of stress roughening and smoothing, in the activity switching dynamics on the network and in the nature and configuration of the failure modes.

In a paper that was summarized in the abstract volume, Professor Sornette (talk was cancelled due to last minute cancellation of Professor Sornette's attendance) described the progress made recently by his group in three areas:

1) The regime of large velocity friction.
2) The critical earthquake concept.
3) The introduction of the wavelet tool in the form of a kalmau filter to the problem of data assimilation in the presence of power law noise.

1) In the regime of large velocity friction the author cites experiments that indicate an increased production of sound waves at higher velocities, which dissipate a large amount of energy. This increased dissipation by sound waves effectively increases the friction. The author interprets this to mean that the Ruina-Dieterich friction laws cannot be extended into the high velocity regime relevant for earthquakes.

2) Performing tests on rock burst data from deep South African mines the author argues that the data gives additional support to the critical earthquake concept. In addition, a new algorithm based on a space-time smoothing indicates the presences of log-periodicity.

3) The author also discussed the application of wavelet analysis and the Kalman-Levy filter to data sets obtained from various sources. In particular the author discusses the case where errors and noise have heavy tail distributions such a power laws and levy laws. The optimal Kalman-Levy filter is found to deviate substantially from the standard Kalman-Gaussian filter as the exponent that characterises the tail of the distribution decreases from the Gaussian value of 2.