The APEC Cooperation for Earthquake Simulation (ACES)

Peter Mora, Mitsuhiro Matsu'ura, Xiang-Chu Yin and Bernard Minster

APEC Cooperation for Earthquake Simulation (ACES)

Originating Economy: Australia
Co-sponsoring Economies[1]: China, Japan, USA

Prof. Peter Mora
Coordinator, ACES proposal
Director, Queensland University Advanced Centre for Earthquake Studies (QUAKES)
Department of Earth Sciences,
The University of Queensland
Brisbane, 4072, **Australia**
Tel: (61-7) 3365 2128
Fax: (61-7) 3365 7347
E-mail: mora@earthsciences.uq.edu.au

Prof. Xiang-Chu Yin
Center for Analysis and Prediction
State Seismological Bureau (SSB)
Beijing, 100036, **China**
E-mail: yinxc@sun.ihep.ac.cn
Tel: (86-10) 6821 5522 (ext. 2715)
Fax: (86-10) 6821 8604

Prof. Mitsuhiro Matsu'ura
Director
Crustal Activity Modelling Program (CAMP)
Department of Earth and Planetary Physics
University of Tokyo
Bunkyo-ku, Tokyo 113, **Japan**
E-mail: matsuura@geoph.s.u-tokyo.ac.jp
Tel: (81-3) 3812-2111 (ext. 4318)
Fax: (81-3) 3818-3247

Prof. Bernard Minster
Systemwide Director, IGPP
Vice Chair, SCEC
Scripps Institution of Oceonography
Univ. California
San Diego, CA, 92093, **USA**
E-mail: jbminster@ucsd.edu
Tel: (1-619) 534-5650
Fax: (1-619) 534-2902

[1]Co-sponsoring economies confirmed during the ISTWG Meeting in Singapore on October 1, 1997.

Summary

Earthquakes are one of the most costly and deadly natural disasters. APEC member economies are struck by the vast majority of the world's earthquakes and have a particularly high earthquake risk. The scientific method relies on development of a theoretical framework or simulation model describing nature. While no such model exists for the complete earthquake generation process, conceptual developments in understanding earthquake physics, numerical simulation methodology and advances in High Performance Computing offer the possibility to develop such models. The APEC Cooperation for Earthquake Simulation (ACES) would capitalize on this new opportunity and the complementary strengths of the earthquake research programs of individual APEC member economies. It aims to develop numerical simulation models for the complete earthquake generation process, to assimilate new earthquake observations into such models, to foster collaboration between the relevant programs of participating member economies, and to foster development of required research infrastructure and research programs. Development of such simulation models represents a grand scientific challenge because of the complexity of phenomena and range of scales involved from miscoscopic to global. The models would provide powerful new tools for studying earthquake precursory phenomena and the earthquake cycle. They would have direct application to earthquake hazard studies and earthquake engineering, and the potential to yield spinoffs in sectors such as mining, geophysical exploration, high performance computing, material science, engineering and geotechnical.

Overview

Preamble

An overwhelming majority of the world's earthquakes strike APEC member economies which are located around the Pacific Plate or in adjacent regions. This has resulted in more than 800,000 deaths in APEC member economies of the approximately 1.3 million deaths associated with earthquakes this century. A seismicity map is shown in Figure 1 and some costly and deadly earthquakes are presented in Tables 1 and 2.

Science uses observations to develop a theoretical framework or simulation model describing nature (e.g. Global Circulation Models). No such model exists for the complete earthquake generation process.

A physically-based numerical simulation capability would be a new powerful tool for studying earthquake precursory phenomena. The development of such a model represents a grand scientific challenge because of the complexity of phenomena and range of scales involved. Specifically, earthquake generation is controlled by a vast range of physical processes occurring over tens of orders of magnitude of scales in space and time as illustrated in Figure 2. Of fundamental importance is the mesoscale, connecting the microscopic and macroscopic realms, because this is where the earthquake nucleation process occurs. This scale is difficult to access with direct observations.

Conceptual developments in understanding earthquake physics, numerical simulation methodology and advances in High Performance Computing offer the possibility to develop complete models for the earthquake generation process.

There are complementary strengths in earthquake research and observational networks in APEC member economies. This initiative provides an opportunity for synergy through co-operation between individual programs of APEC member economies. It has been developed during the last three years as a result of interactions between scientists and research groups in Australia, Chile, China, Indonesia, Japan, Mexico and USA. On 12-15 August 1997, a meeting was held in Australia with participation from China, Japan and USA to discuss the collaboration and develop a framework for organisation of activities, management structure and the process to establish the project (note: Indonesia accepted an invitation to participate but was unable to do so due to illness). Scientific representatives of participating member economies in attendance were:

Australia

Prof. Peter Mora
ACES Proposal coordinator and
Director, QUAKES
The University of Queensland, Brisbane

China

Prof. Xiang-Chu Yin
Centre of Analysis and Prediction
State Seismological Bureau
Beijing, 100036

Japan

Prof. Mitsuhiro Matsu'ura
Director, Crustal Activity Modelling Program
Department of Earth and Planetary Physics
University of Tokyo

USA

Prof. Bernard Minster
Systemwide Director
Institute of Geophysics & Planetary Physics (IGPP)
Vice Chair, SCEC
Scripps Institute of Oceanography
University of California, San Diego

Official governmental observers and advisors in attendance were: Prof. Michael Pitman (Advisor: Department of Industry, Science & Tourism, Australia; and Foreign Secretary: Australian Academy of Sciences); and Prof. Guomin Zhang (Vice-Director: Centre of Analysis and Prediction, State Seismological Bureau, Beijing, China). Mr. Brian Delroy (Director: APEC/Asia Section and Acting Assistant Secretary: International Science and Technology Branch, Department of Industry, Science and Tourism, Canberra, Australia) was also available for consultation during the course of the meeting.

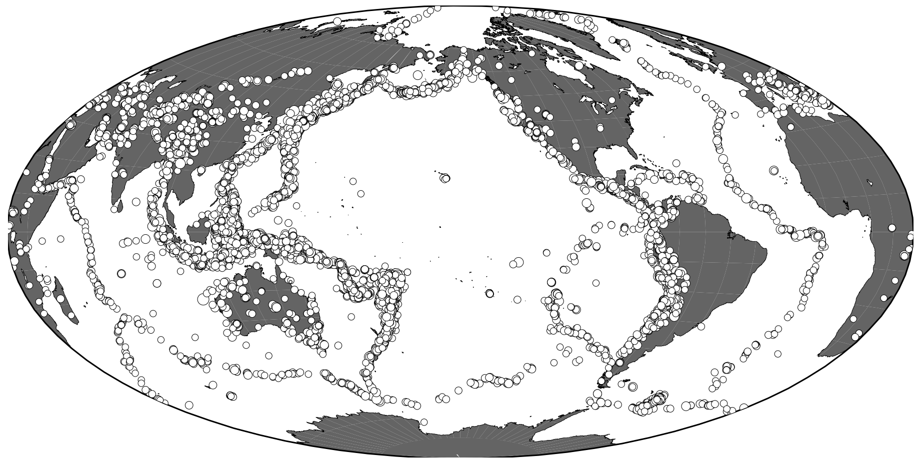


Figure 1: Plot of locations of earthquakes this century with magnitude greater than 5.

Objectives

The objectives of the APEC Cooperation for Earthquake Simulation are:

- to develop realistic numerical simulation models for the physics and dynamics of the complete earthquake generation process and to assimilate new earthquake observations into such models,
- to foster collaboration between the relevant complementary programs of participating member economies, and
- to foster development of the required research infrastructure and research programs.

Participating economies

The sponsoring economies[3] are Australia, China, Japan and USA. Participation by other member economies would be welcomed.

Management structure

See Appendix A for an organisational diagram.

The **Executive Director** will be responsible for the management of the Project including implementation of the strategic goals, administration, education and outreach activities, and resource management. He/she will be nominated at an initial meeting of the representatives of participating economies and will be an ex officio member of the International Science Board. The Executive Director will report to the ISTWG and through that, to Regional S&T Ministers on progress of The Project. Executive powers will be specified in the by-laws established by the International Science Board.

[3]As confirmed at the ISTWG Meeting in Singapore on October 1, 1997.

Country	Year	Mag	Deaths/ Missing	Comments
Indonesia	1996	8.1	138	US$ 60 million damage, 5,043 houses destroyed
Japan	1995	6.9	5,502	US$ 58 billion direct damage
USA	1994	6.6	61†	US$ 10 billion insured losses
Indonesia	1992	7.6	2,004	US$ 120 million damage
Philippines	1990	7.8	1,621	
Australia	1989	5.6	14	1-st deadly Australian quake‡ Est. AUS$ 4 billion total losses
USA	1989	7.1	62	US$ 6.8 billion direct damage, 12,000 homeless
Mexico	1985	8.1	9,500	
Philippines	1976	7.9	8,000	
China	1976	8.0	255,000	
New Guinea	1976	7.1	9,000	
USA	1971	6.5	58	US$ 500 million damage
USA/Alaska	1964	9.2	131	US$ 312 million damage
Chile	1960	9.5	5,000	
Japan	1948	7.3	5,390	
Chile	1939	8.3	28,000	
USA	1933	6.3	120	Lead to "Field Act"
China	1927	8.3	40,000	
Japan	1923	8.3	143,000	
China	1920	8.6	245,000	
USA	1906	8.25	700-2,500	$US 400 million damage
Chile	1906	8.6	20,000	

Table 1: Selection of deadly earthquakes this century (sources: USGS; EQE; SSB; MGA; Bolt, 1993). † It has been suggested that the death toll for the 1994 Northridge earthquake would have been in the thousands had it not occurred in the early morning of a public holiday. ‡ Much larger earthquakes have been recorded in Australia - up to a similar size as the magnitude 6.9 earthquake that struck Kobe, Japan in 1995.

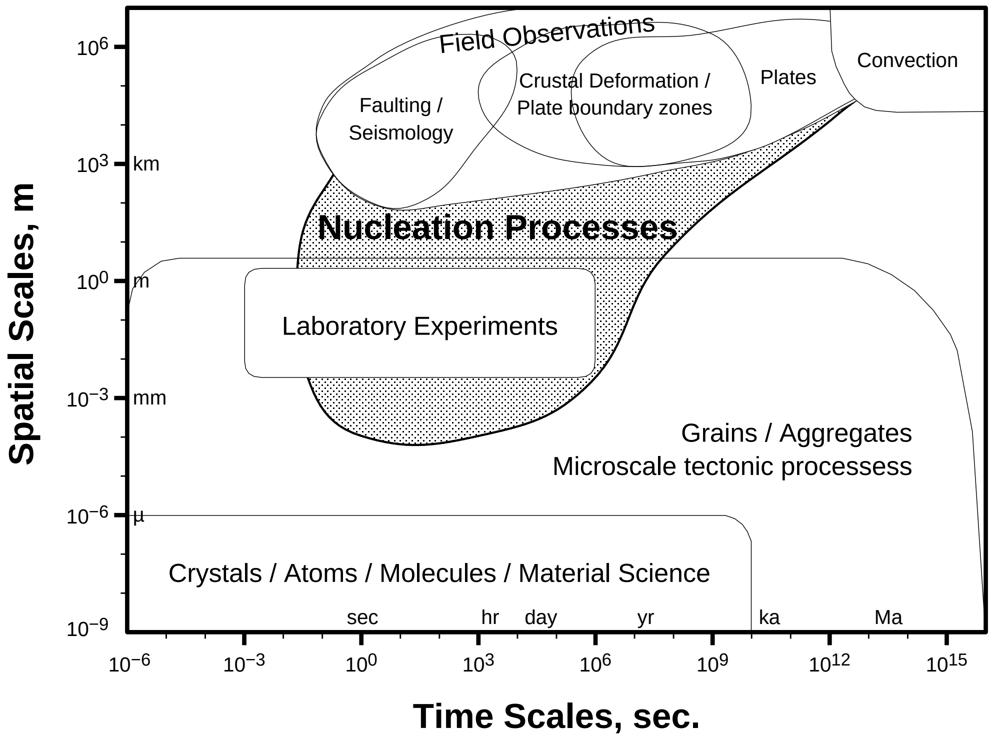


Figure 2: Space and time scales relevant to the earthquake cycle. Physical processes occurring at the microscopic scale (Grain/Aggregates Micro-tectonic processes) control the earthquake generation process. This domain is only partially accessible by direct observations. The meso-scale where the earthquake nucleation process occurs is difficult to access with direct observation and lies between the microscopic and macroscopic realms. Note: The boundaries between the different domains on the plot are fuzzy. They are represented as sharp lines only to enable Fax transmission of the plot.

	Magnitude	Insured loss US$m	Date
Japan	6.9	n.a.*	Jan 1995
United States	6.6	10,000	Jan 1994
United States	7.1	920	Oct 1989
Australia	5.6	670	Dec 1989
Mexico	8.1	280	Sep 1985
New Zealand	6.3	270	Mar 1987
Guam	8.1	160	Aug 1993
Philippines	7.8	110	Jul 1990
Iran	7.4	100	Jun 1990
Chile	7.7	90	Mar 1985

Table 2: Largest earthquakes by insured loss, 1984 - 1994 (source: Re-insurance industry as published in The Economist, 21/1/95) plus the 1995 Kobe earthquake (source: USGS). Notes: (1) Insured losses normally represent a fraction of total losses (typically about 25% or less), (2) $ amounts given are those printed at time of publication and are not adjusted for inflation. * Repair cost estimates for Kobe due to this earthquake excluding indirect damage were US$ 95 - US$ 147 billion (source: EQE) and up to US$ 185 billion. Kobe City direct damage is reported as 6.9 Trillion Yen or approx. US$ 58 billion (source: http://www.kobe-cufs.ac.jp/kobe-city).

An **International Science Board** consisting of one representative nominated by each participating member economy would develop by-laws and a proposed program of activities including identification of collaboration. Each board member would have responsibility for coordinating between The Project and the relevant research programs, centres and consortia of the member economy being represented. The Chairman will be appointed according to the by-laws established by the Board. Voting rights, rules and procedures of the Board, will be decided at an initial meeting of the representatives of the participating economies.

Science Working Groups would be established by the International Science Board to address the different components of the scientific problem.

Standing Committees would be established as the need arises to address non-scientific issues that may need to be resolved to achieve the goals of The Project.

Project timetable

See Appendix B.

Participants role

Participating member economies would be responsible for nominating a representative to the International Science Board who would be the liaison between ACES and the activities of the member economy associated with The Project.

Synergies and programs

The Project description and methodology is summarized in Section . A detailed scientific program will be developed by the International Science Board during the first year of The Project. The brief summary of the programs of sponsoring economies and key research areas of ACES provided below gives an indication of the synergies that would be developed by establishment of The Project.

Programs of sponsoring economies

Australia

- Large earthquakes occur in Australia, although less frequently than many other APEC member economies.

- Australian cities are highly vulnerable to the earthquake hazard due to insufficient mitigation measures and being frequently built on sediments which are subject to amplification.

- The 1989 magnitude 5.6 Newcastle event was small by international measures but caused loss of life and major damage (estimated at AUS$ 4 billion in total losses).

- Sparse seismic networks and little data mean that the earthquake hazard is poorly quantified.

- New technology and approaches are required to allow the earthquake hazard in Australia to be well understood and quantified.

- QUAKES is focused on filling a fundamental gap in the knowledge of the earthquake process by developing a microscopic based numerical simulation capability. The Centre's program

  - aims to provide information on a variety of scales relevant to the earthquake generation process, and particularly in the microscopic realm where the underlying physical mechanisms that control earthquake nucleation occur,
  - aims at gaining an understanding aggregate behavior of rocks and faults zones,
  - has available a dedicated state-of-the-art parallel supercomputer for earthquake simulation research (3.1 GFlops Silicon Graphics Origin 2000) and high performance graphics stations.

China

- High frequency, large magnitude, shallow depth earthquakes occur over a widely distributed area. 70% of large cities with a population of more than 1 million people will experience seismic intensity of 7 and above on the Modified Mercalli Intensity Scale. This leads to a serious level of seismic hazard.

- Long history of seismic data and earthquake prediction program (since 1966) and observations of seismic precursory data (more than 100 earthquake cases, $M_s > 5$ with multidisciplinary observations), some experimental methods and preliminary models (e.g. LURR model) of earthquake prediction.

- It is essential to understand the seismogeneous process and precursory mechanism with large-scale computer simulation.

Japan

- Japan is located in a complex tectonic setting; interaction of four plates (Pacific, North American, Eurasian and Philippine Sea Plates).
- There is a well-understood seismic and tectonic environment including:
  - crustal structure,
  - active fault distributions,
  - 3D geometry of plate boundaries,
  - historical records of earthquakes,
  - seismic activity data from dense seismic networks, and
  - crustal movement data from dense geodetic networks,
- Long history of earthquake prediction research (1963 - now) supported by many institutions.
- Need to understand the physical processes of earthquake generation.
- Need large-scale computer simulation based on a realistic physical model.
- Japan commenced the Crustal Activity Modelling Program (CAMP) in 1997.
- Japan is one of a few places in the world where we can test the performance of computer simulation models through direct comparison with observed seismic, geodetic, and tectonic data.

USA

- Three large earthquakes in the last 10 years: Loma Prieta (1989), Landers (1992) and Northridge (1994) with two of these in urban areas (Loma Prieta & Northridge). All three events were uncommonly well recorded and studied.
- Earthquake research is supported by a number of institutions and programs:
  - NEHRP: National Earthquake Hazards Reduction Program (NSF, USGS, FEMA, NIST),
  - Southern California Earthquake Center[4] (SCEC),
  - Incorporated Research Institutions for Seismology (IRIS).
- Earthquake research is well developed at a national and regional level.

[4] Multi-institution research center. Principal institutions: California Institute of Technology; Columbia University; United States Geological Survey; University of California, Los Angeles; University of California, San Diego; University of California, Santa Barbara and University of Southern California.

- Existence of SCEC - multidisciplinary approach to understanding the earthquake problem. Expertise:
  - Multi-institution, multi-disciplinary approach,
  - Education and outreach experience.
- Recent growth in high performance computing initiatives - NPACI, ASCI. Proposal to use this expertise to study earthquake processes - General Earthquake Model (GEM).
- West coast is heavily instrumented - vast amount of data available.
- Only a few places in the world (i.e. Japan and California) that have a detailed range of seismic, geodetic and geological data available for comparison.

Key research areas envisaged for ACES working groups

Microscopic models

Earthquake generation and nucleation is controlled by microscopic physical processes from molecular to rock grain scales and above. These involve evolving discontinuities (fractures) and interactions between a complex set of physical processes.

A new numerical model termed the lattice solid model has been developed at QUAKES in Australia with the potential to simulate the required level of geometric complexity and range of physical processes. It is based on molecular dynamics principles to model interacting particles by numerically solving their equations of motion but particles may represent larger units or aggregates of molecules such as grains or blocks of rock.

When fully developed to incorporate the full spectrum of relevant physical processes[5] and realistic geometrical complexity[6], the lattice solid model has the potential to allow the underlying microscopic processes controlling earthquake nucleation to be simulated with a high degree of realism. Feedback and comparison with laboratory and field observations will be crucial in the development and refinement of this simulation model. This will be provided through interactions with participating laboratory groups in China, Japan and USA and through the Data Assimilation Working Group of ACES.

While the microscopic based approach could in principle simulate earthquake generation at larger than microscopic scales, it is limited by resolution (i.e. number of particles that could be simulated). Hence, it is crucial to concurrently develop macroscopic domain methodology. A framework is provided by classical elasticity but this neglects the relevant physics controlling fault behavior and nonlinear response of rocks due to a wide spectrum of physical processes of relevance (e.g. “stress corrosion”). Hence, new constitutive relations describing rock and fault zone behavior are required. Microscopic domain simulation studies in conjunction with laboratory experiments would provide the basis for developing these new constitutive relations and a theoretical understanding of “course graining”.

[5] Elastic stress transfer, finite strain, friction, fracture, granular dynamics, thermal effects, fluids, phase transitions, molecular, chemical, electro-magnetic, piezo-electric etc.

[6] Complex evolving and discontinuous 3D geometries with arbitrary heterogeneity, interactions over a wide range of scales etc.

Macroscopic models

Realistic macroscopic domain simulation is a key requirement to develop an understanding of the complete earthquake generation process and would also provide a powerful tool for scenario earthquake modelling[7].

The Crustal Activity Modelling Program (CAMP) of Japan commenced in 1997 and is aimed at modelling the earthquake generation process at the crustal scale. It involves a multi-disciplinary effort between earth sciences and computer science and uses classical elasto-dynamical theory as the basic framework from which to develop the crustal scale modelling capability. This involves theoretical, conceptual and numerical developments that allow the large scale simulation capabilities to be developed. Crucial ingredients are development of parallel algorithms, approaches to model complex fault geometries, and incorporation of new constitutive relations that adequately describe fault zone and rock behavior over the range of space and time scales being considered. Feedback with the microscopic simulation program and laboratory groups would be essential for the development and refinement of these constitutive relations.

A project called GEM[8] with similar goals to CAMP has been proposed in the USA involving a strong multi-disciplinary multi-institution[9] group of seismologists, material scientists, physicists and computational scientists. The GEM or General Earthquake Model project aims to develop large scale massively parallel simulations of large numbers of interacting earthquake fault systems. This project is compared to the program of numerical simulation to understand the weather and climate using Global Circulation Models (GCM's).

The macroscopic simulation groups that have formed in Japan and USA have complementary strengths. Furthermore, Japan and USA have developed the most detailed data sets worldwide that will provide a critical resource to allow the simulation models to be validated and refined.

Data assimilation

A core activity of ACES will involve data assimilation to ensure the numerical models yield results that match the available observations. Specifically, the microscopic simulation results must be compatible with laboratory observations and the macroscopic simulation results must yield phenomenology that is consistent with field observations.

The rich sets of observations available in the different tectonic settings of China, Japan, and California will provide an invaluable resource allowing the earthquake simulation models to be developed and validated. The goal is to continually refine the theoretical simulation models as additional data becomes available.

---

[7] Scenario earthquake modelling provides detailed estimates of ground shaking due to specific hypothetical earthquakes. This information would enable earthquake engineers to design safer structures.

[8] The GEM group is coordinated by Prof. John Rundle, Director of the Colorado Centre for Chaos and Complexity.

[9] U. of Colorado; M.I.T.; CalTech; U. of California, San Diego; USGS; Cornell U.; Boston U.; Santa Fe Institute; Syracuse U. and Northeastern U.

Nonlinear models

Preliminary nonlinear models describing aspects of earthquake behavior that have been developed and appear to match some observations must also be explained. The numerical simulation capabilities developed by ACES would allow these to be refined. For example, in China, the State Seismological Bureau has developed relatively successful approaches for intermediate term earthquake forewarning in the 1 year time frame. These are based on microphysically based concepts describing the fault failure cycle. The microscopic numerical simulation capabilities will allow these concepts to be developed and refined. Feedback between the microphysical modelling and macroscopic observations will play a key role in the process of model refinement. In China and the USA, nonlinear models are being developed to study aspects of earthquake dynamics and the earthquake cycle. These models may be tested and validated against the microscopic and macroscopic simulation models.

Scaling

Earthquake nucleation involves physical processes occurring over tens of orders of magnitude in space and time (see Figure 2). Microscopic simulation models approach this domain from below and will allow the underlying microphysical mechanisms controlling earthquake generation to be studied. Macroscopic models using the appropriate constitutive relations will provide a means to study earthquake phenomenology and the nucleation process. A major problem is in linking the two scales. This requires multidisciplinary research involving theoretical, computational and nonlinear science groups, aimed at developing an understanding of course graining and scaling issues.

Planned results and relevancies

Results

The Project aims to develop realistic numerical simulation models for the physics and dynamics of the complete earthquake generation process and to assimilate new earthquake observations into such models.

Relevancies

Strategic importance and relevance to region

The Pacific Rim and adjacent regions are of high earthquake risk as illustrated by Figure 1 and Tables 1 and 2. APEC member economies have suffered the vast majority of deaths and economic losses due to earthquakes this century. Economic losses due to earthquakes have grown rapidly this century as infrastructure has developed. A large earthquake strike of a major financial centre in the APEC region has the potential to impact on the APEC economy as a whole.

The key requirement needed to develop strategies aimed at minimizing human and economic losses due to earthquakes is a comprehensive understanding of the earthquake cycle. ACES aims to develop numerical simulation models which would provide powerful new tools to gain this understanding.

Benefits to member economies

Numerical simulation models developed through ACES would provide the means to gain an improved understanding of the earthquake cycle and hazard. This information would facilitate the development of effective plans and strategies for sustainable economic growth, and to protect populations, in the presence of the earthquake hazard.

The specific outcomes and socio-economic benefits to APEC member economies that could potentially be achieved through ACES are:

1. New understanding of earthquake precursory phenomena and hazard that may allow measures to be developed that substantially decrease economic and human losses due to earthquakes, and minimize perturbations to the APEC economy,

2. Improved capabilities for scenario earthquake modelling that would provide earthquake engineers with the information needed to design safer structures and allow more effective earthquake mitigation measures to be developed,

3. Methodology that may facilitate development of other natural hazard simulation models (e.g. volcanos, landslides, liquefaction, etc),

4. Science and technology spinoffs in sectors such mining, geophysical exploration, high performance computing, material science, engineering and geotechnical.

Relevance to APEC action plan and ISTWG action plan

The APEC Cooperation for Earthquake Simulation has been developed by a multidisciplinary group of leading international scientists from APEC member economies. Due to the socio-economic significance of The Project to member economies, it is most appropriate for it to be developed as an international scientific cooperation under the umbrella of APEC.

ACES is relevant to the APEC Action Plan through the third pillar of the APEC Agenda: *Economic and Technical Cooperation* specified in the Bogor Declaration of Common Resolve on 15 November, 1994 because it involves *"intensified development cooperation to attain sustainable growth, equitable development, and national stability"*. ACES matches with the vision, goals and priorities of the *Common Policy Concept* of the *Osaka Action Agenda* as detailed below.

Vision

The ISTWG vision *"for the 21-st century is of a dynamic and prosperous Asia-Pacific region built on the development and application of industrial science and technology which improves quality of life ..."*.

This requires management of the environment including development of appropriate safeguards against natural hazards which may result in human losses and suffering or affect the region's economy. The earthquake natural hazard is of major concern to the APEC region where the vast majority of the world's earthquakes occur.

Development of effective strategies to minimize the impact of the earthquake hazard requires industrial application of soundly based scientific knowledge of the earthquake generation process and earthquake cycle. Development of this knowledge requires a theoretical framework or simulation model describing the complete earthquake generation process as well as assimilation of observed data into this model. This is the mission of The APEC Cooperation for Earthquake Simulation.

Goals

The APEC Cooperation for Earthquake Simulation is consistent with three of the eight goals of the ISTWG as stated in the *Osaka Action Program*. Namely,

4. Improved levels of scientific knowledge promoting economic activities, particularly private/business sector growth, as well as technological sophistication in the region;

    The scientific knowledge resulting from ACES will promote sustainable economic growth by provision of key information needed for the development of sound measures to mitigate against the potentially catastrophic earthquake hazard.

7. Enhanced links ...

    ACES will foster enhanced links between governmental agencies and academic institutions involved in The Project.

8. Efficient and effective support for industrial science and technology cooperation projects and programs.

    The endorsement of ACES by the ISTWG is a key step towards developing ongoing support of this grand challenge international cooperative science project.

Key priorities

The endorsement and establishment of ACES is consistent with 4 of the 6 key priorities set out by the Osaka Action Agenda for effective science and technology collaboration. Namely, it would lead to:

- Improve Flows of Technological Information on the earthquake generation process and numerical simulation of the associated physical processes and high performance computing concepts,
- Improve Researcher Exchange,
- Facilitate the development of Joint Research Projects,
- Contribute to sustainable development (see also Section)

Relevance to the private sector and non-governmental organisations

ACES has relevance to the private sector through The Project's potential to yield regional socio-economic benefits and S&T spinoffs as summarized in Section .

Statement of cross-linkages

ACES is unique. It would link the relevant earthquake programs in participating member economies and provide an opportunity for synergies to develop between these complementary efforts.

It involves participation of forefront numerical simulation and nonlinear studies groups including:

- Australia: QUAKES - microscopic scale simulation/lattice solid approach;
- China: CAP/SSB/SSTC & LNM/CAS - experimental intermediate term prediction models/nonlinear groups;
- Japan: CAMP - Crustal Activity Modelling Program.

  CAMP aims to construct a physically based numerical model for earthquake generation including tectonic stress accumulation, quasi-static nucleation and subsequent dynamic rupture propagation;

- USA:
  - SCEC: grouping of universities and research institutions pursuing multi-disciplinary earthquake research,
  - GEM: multi-disciplinary project to develop a General Earthquake Model for modelling complex fault systems,
  - Harvard University: earthquake theory and modelling group,
  - Lamont-Doherty Earth Institute: Center for Nonlinear Earth Systems.

The Project would be conducted in collaboration with observational groups of participating member economies. It is complementary to the USA proposal to the APEC ISTWG for "Earthquake Loss Estimation Methodology", having the potential to lead to methodology for improved earthquake hazard estimates including earthquake scenario modelling. The Project falls within the framework of the proposal from Japan to the ISTWG for "Collaborative Research on Disaster Prevention (with particular focus on earthquake disasters)" but is more specific, proposing to capitalize on a new opportunity offered by advances in supercomputer and numerical simulation concepts to study the complete earthquake generation process.

The Project falls within the framework of goals of the International Decade for Natural Disaster Reduction (IDNDR) program.

Funding requirements

- The Project would largely be self funded by participating economies.
- An initial operating fund will be established by member contribution. An initial amount of $US 20,000 per member economy will secure participation in ACES during the first year including membership on the International Science Board. To ensure representation on the International Science Board during the by-law development phase, confirmation of participation will be required within one

month of The Project's endorsement by the ISTWG[10]. These pooled funds will cover administrative costs of the executive office in establishing an International Science Board, developing by-laws, and to identify ongoing requirements and funding resources.

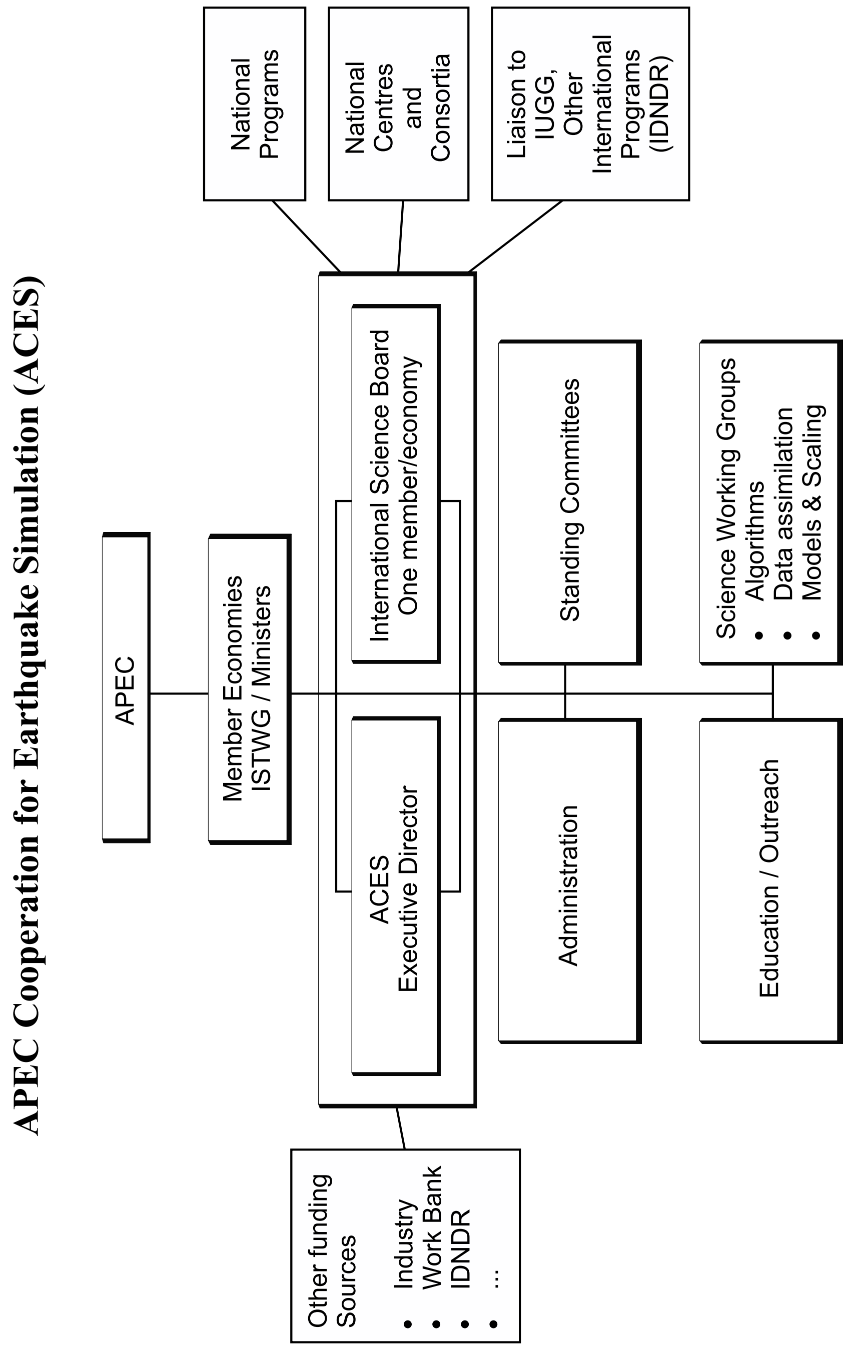
- Longer term funding would be sought by a combination of member contributions, private sponsorship, and international organisations and programs (e.g. World Bank, IDNDR etc).
- APEC funds will not be sought in the first year but a proposal for funding may be developed for 1999.

Plans for information dissemination

ACES would produce an annual progress report summarizing principal research findings. This would be distributed to the appropriate agencies of participating APEC member economies. Regular workshops would be convened to present the results and foster enhanced collaboration and facilitate exchange of ideas (a yearly basis for workshops is envisaged). An internet home page would be established to facilitate information dissemination. One of the functions of the executive branch would be education and outreach. This would include activities such as publication of materials, press interactions and oral presentations at the appropriate forums. These activities would draw on the experience at SCEC which has a specific education and outreach program and QUAKES which has extensive experience in disseminating information to industry, local community groups and Federal, State and Local government agencies.

[10] Such a confirmation should include a committment to pay the initial membership dues of $US 20,000.

Appendix A: Organisational diagram



Appendix B: Project timetable

	1997	1998	1999	2000	2001
1. Framework as basis for evaluation[1]	___				
2. Proposal put to APEC ISTWG[2]	*				
3. Identification of members and representatives[3]	.........__				
4. Specification of process and identification of collaboration[4]		_____			
5. Inauguration[5]		*			
6. Co-operative Programs		__	________	________	________
7. Visitor Programs and Workshops[6]		X	_____X	_____X	_____X
8. Review[7]					X

[1] A meeting held in Australia 12-15th August 1997, with participation from Australia, China, Indonesia, Japan and USA, discussed collaboration in earthquake simulation and developed a framework for organisation, activities and the process to establish the Project.

[2] A document endorsed by the sponsoring economies will be developed and submitted to ISTWG at Singapore in October 1997.

[3] Representatives for an International Science Board and an Executive Director will be nominated by member economies. Participating institutions/agencies identified.

[4] The International Science Board will draw up the articles and procedures and a program of activities, including identification of collaboration.

[5] An opportunity will be sought for a launch or inauguration, possibly at the S&T Ministers meeting or Leaders meeting.

[6] Visitor exchanges and Workshops will be planned based on opportunities and funding.

[7] A review would be undertaken after three years.

Outcomes of the inaugural meeting of the ACES International Science Board

May 4-8, 1998

The Inaugural ISB Meeting agenda and attendees

The inaugural meeting of the ACES International Science Board (ISB) was held to conduct scientific planning and establish the organisational framework such that activities and operations could commence. Items on the agenda were:

1. Specification of the Science Plan,
2. Specification of Working Groups,
3. Specification of a Program of Activities,
4. Development of By-Laws including provision for new membership,
5. Nomination of Executive Director,
6. Organisational and operational framework,
7. Identification of ongoing funding requirements and resources.

Present at the meeting were: Associate Professor Peter Mora, ACES coordinator and ISB member (Australia), Professor Xiang-chu Yin, ISB member (China), Professor Mitsuhiro Matsu'ura, ISB member (Japan), Dr. Miriam Baltuck[1], NASA representative in Australia (representing Dr Jim Whitcomb, ISB member, USA), and Mr Brian Delroy[2] , APEC ISTWG representative of the Australian Federal government. Present at the farewell dinner were: Associate Professor Peter Mora; Professor Xiang-chu Yin; Professor Mitsuhiro Matsu'ura; Mr Brian Delroy; Professor Paul Greenfield (Deputy Vice Chancellor Research, The University of Queensland); Dr Bob Day (Director-General, Queensland Department of Mines and Energy); Mr Michael Otago (Senior Executive, Queensland Department of Economic Development and Trade) and Evelyne Meier (Hostess).

[1]Present on Wednesday evening and Thursday only.
[2]Present on Friday only.

1. Science Plan

1.1 Summary

The ACES Science Plan is to develop physically based numerical simulation models for the complete earthquake generation process and to assimilate observations into these models. The models aim to simulate all physical and chemical processes in the Solid Earth at all time and space scales relevant to the earthquake cycle. The final goal is to develop a unified simulation model for the earthquake generation process and earthquake cycles in the Asia-Pacific region. This model will consist of regional models in each of the different tectonic settings:

- Transcurrent regimes or transform plate boundaries (e.g. California, New Zealand),
- Subduction zones (e.g. Chile, Mexico, Alaska, Kurils, Japan, Indonesia),
- Intraplate regions or continental plates (e.g. Australia, China, central and eastern USA).

The simulation models will provide a new means to probe earthquake behaviour and the associated physical processes. They will allow theoretical forecasts of the earthquake cycle and related processes to be computed. This capability represents a powerful tool for the development of new models applications and improved earthquake data analysis systems.

The Science Plan will be achieved through the activities of five Working Groups (see Section 2) termed WG1 through WG5. These consist of researchers from participating research groups of the Participant Economies. Figure 1 illustrates the feedback process that will ensure the simulation models are developed such that their theoretical forecasts (e.g. of the earthquake cycle, etc.) are compatible with, and constrained by, the observed data. It also shows how the theoretical forecasts will provide input to allow new models applications to be developed. These models applications will also be refined through a feedback process that ensures their predictions are compatible with observations. Figure 2 provides additional detail of the different components of Figure 1 and illustrates an internal feedback process involving the three elements (microscopic, macroscopic, and computational) of the ACES core program to develop physically based numerical simulation models. Figure 3 illustrates how ACES adds to, and is complementary with, the pre-existing earthquake prediction and/or hazard quantification programs and systems, which are based on data gathering and analysis.

1.2 Potential evolution

In the present phase, ACES is focussed on construction of a unified simulation for earthquake generation and the earthquake cycle in the Asia-Pacific. This goal requires the development and combination of simulation models for many (but not all) physical processes in the Solid Earth, and specifically in the crust and lithosphere. Hence, it is logical to envisage a subsequent phase in which ACES is expanded to include simulation of the remaining physical processes in the Solid Earth such as

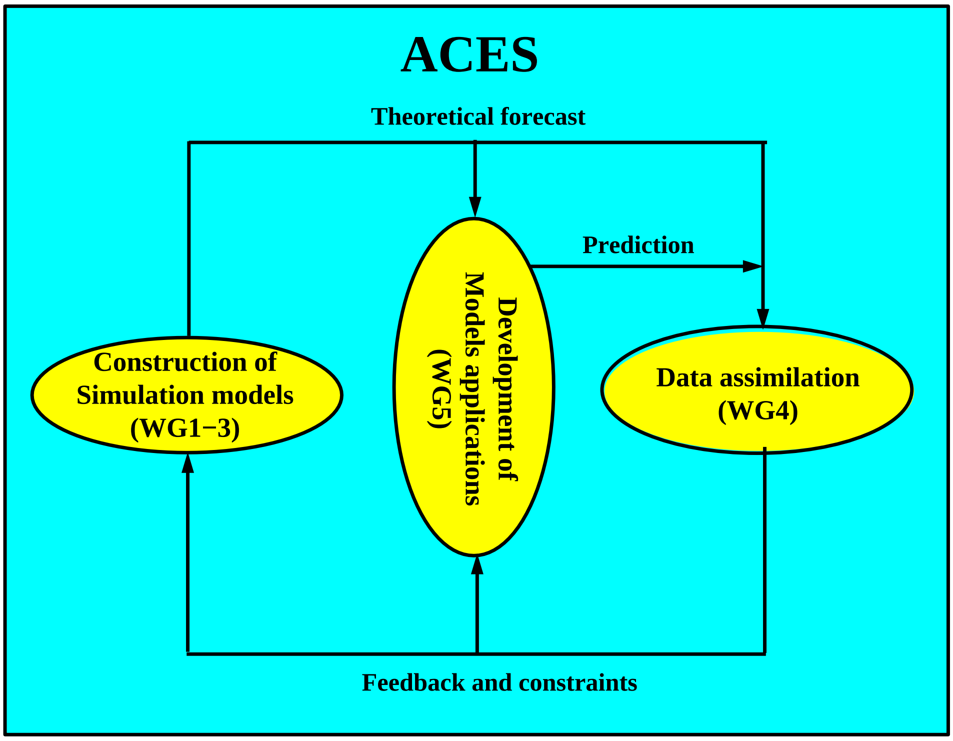


Figure 1: Illustration of the ACES Science Plan to develop realistic numerical simulation models for the complete earthquake generation process and to assimilate observations into such models. The diagram depicts the feedback process that will allow the models to be developed such that they yield theoretical forecasts (of the earthquake cycle, etc.) which are compatible with, and constrained, by the observed data. It also shows how the theoretical forecasts will provide input to allow new applications to be developed, which will be refined through a similar feedback process.

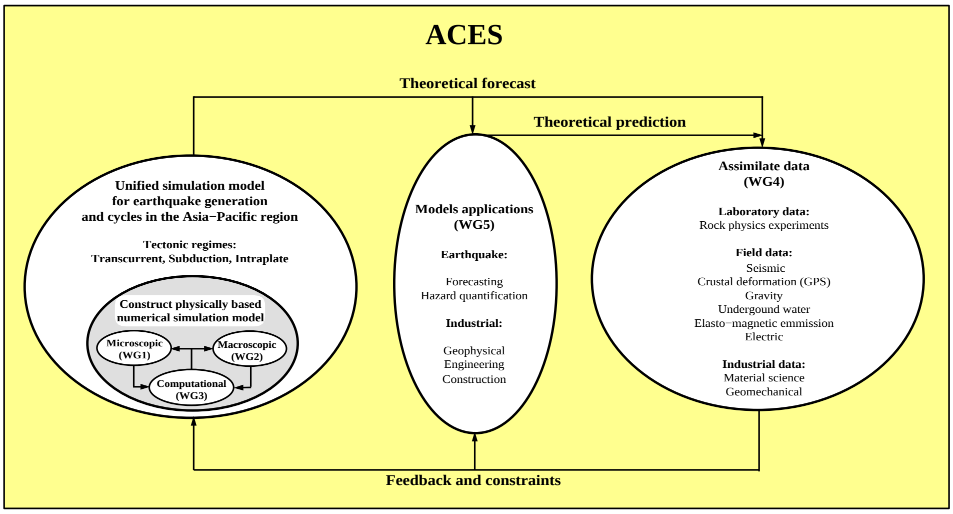


Figure 2: Illustration of the ACES Science Plan depicted in Figure 1 providing additional details including an internal feedback process between the Microscopic Simulation, Macroscopic Simulation and Computational Working Groups.

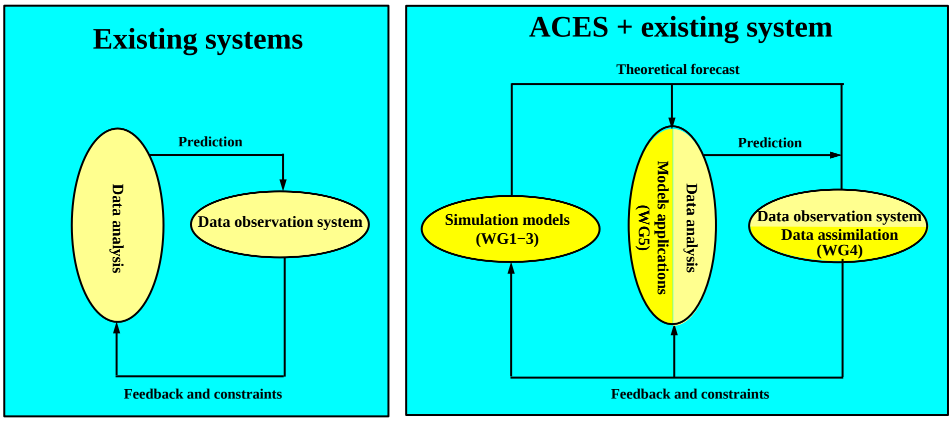


Figure 3: Illustration of how ACES adds to, and is complementary with, the pre-existing earthquake prediction and/or hazard quantification programs and systems, which are based on data observation and analysis.

mantle convention, core dynamics as well as any additional processes in the crust not yet included in the simulation models (e.g. mountain building). This would be achieved by expanding the scope of ACES and combining with the Mantle and Core simulation communities under a single framework. As a long-term vision, it is envisaged that the ACES II Solid Earth Simulation System should be unified with the Ocean/Atmosphere Simulation Systems developed by the "Fluid Earth" simulation community by combining these under a single framework. The present and two subsequent potential phases of ACES are therefore:

- **ACES I: Simulation of the Earthquake Generation Process and Earthquake Cycle**

  Construct physically based numerical simulation models for earthquake generation and the related physical processes with the ultimate goal of constructing a unified simulation model for earthquake cycles in the Asia-Pacific region.

- **ACES II : Simulation of the Solid Earth System**

  Construct a unified model to simulate all processes in the Solid Earth including all crustal processes, mantle convection and core dynamics.

- **Phase III: Simulation of the Whole Earth System**

  Unification of the Solid Earth Simulation System of ACES II and the Ocean/Atmosphere Simulation Systems.

These phases are illustrated in Figure 4.

2. Working Groups

The Science Working Groups identified include three that relate to the construction of physically based numerical simulation models for the earthquake generation process. These are Microscopic Simulation Models, Macroscopic Simulation Models and Computational Methods/Algorithms. These three Working Groups are closely coupled as illustrated in Figure 2 and represent the core of ACES. A fourth Working Group aims to ensure data is assimilated into the numerical models either through provision of constraints such as crustal movements, or via a feedback process to ensure compatibility of the simulation results with observations. A fifth Working Group aims to use the numerical simulation models as a basis to develop new applications (e.g. earthquake forecasting, hazard quantification and industrial).

2.1 Microscopic Simulation Working Group (WG1)

The Microscopic Simulation Working Group aims to develop microscopic domain simulation models for the elementary physical and chemical processes relating to earthquake generation. This includes three basic aspects.

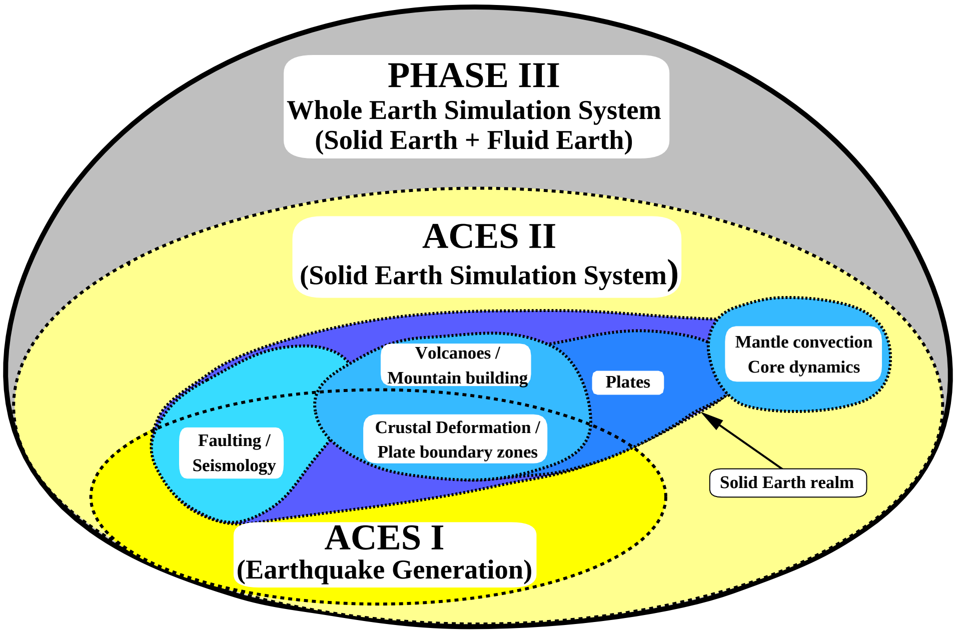


Figure 4: Illustration of the present and two subsequent potential phases of ACES (see also Figure 2 of the ACES proposal to APEC which shows the temporal and spatial scales for the Solid Earth realm portrayed on Figure 4).

2.1.1 Development of simulation models for the elementary physical and chemical processes

Elementary processes in complex fault zones include fracture, friction, effect of fluids, chemical processes, effect of heat, phase transformations, granular flow, non-linear dynamical effects, and effect of geometric complexity (rough surfaces, complex fault gouge, fracture distributions, evolution effects due to changing microstructures).

2.1.2 Issues of scaling from the microscopic realm to the macroscopic realm

The elementary physical and chemical processes involve many spatial and time scales (see ACES proposal to APEC, Figure 2: domain of Grains/Aggregates/Micro-scale tectonic processes). The issue of scaling results across this range of space and time presents a major challenge with finite computational resources and current analytical techniques.

2.1.3 Derivation of fault constitutive laws for realistic fault zones for use by the Macroscopic Simulation Working Group.

Fault zone behaviour is the result of non-linear interactions between the elementary physical processes occurring at many spatial and temporal scales in geometrically complex fault gouge zones. The Microscopic Simulation Working Group will ultimately provide constitutive laws that are applicable for such realistic fault zones. These are not accessible to direct observation. The Microscopic Domain Simulations will be refined through a feedback process ensuring compatibility of theoretical results with laboratory observations where possible (e.g. Figure 2 of the ACES proposal to APEC illustrates an intersection between the domains of "Grains/Aggregates/Micro-scale tectonic processes" and "Laboratory Experiments" where compatibility could be verified).

2.2 Macroscopic Simulation Working Group (WG2)

This Working Group will aim to develop macroscopic domain numerical simulation models for the earthquake generation process (based on continuum mechanics). This includes models for the complete cycle from tectonic loading, quasi-static rupture nucleation, to dynamic rupture and seismic wave propagation. The fault constitutive laws output by WG1 will provide key input for the macroscopic domain simulation models. The macroscopic simulation models can be divided into several groups depending on the time and space scales of the processes being simulated, or goals and regional tectonic settings.

2.2.1 Simulation of the earthquake cycle and crustal movement

- Tectonic loading due to relative plate motion
- Quasi-static rupture nucleation
- Dynamic rupture propagation and stop
- Fault lithification and healing

2.2.2 Simulation of earthquake rupture and seismic wave propagation

- Earthquake generation and dynamic rupture
- Strong motion modelling (wave propagation and amplification)

2.2.3 Seismicity and spatio-temporal patterns

- Interacting faults and fault networks
- Accelerating moment release

2.3 Computational Working Group (WG3)

Working Groups 1 and 2 will be closely coupled with a Computational Working Group aimed at developing common computational methods and algorithms for the simulation models, and common tools and routines for their computation on super-parallel computer systems. Efficient methods, algorithms, routines and tools on super-parallel computer systems will be essential to achieve the goal of simulation of earthquake generation in the Asia-Pacific region which is required for the data assimilation feedback process and application of the models. The Computational Working Group will consist of computational scientists spanning across disciplines including seismology, physics, computer science and mathematics. It will focus on development of algorithms/routines/tools for super-parallel computers such as FFT's and solvers (e.g. banded and sparse matrix solvers, FFTs, etc.) and specific algorithms for the new computational models in the macroscopic or microscopic domains such as:

- For microscopic simulation:
  - Special numerical integration algorithms to handle discontinuities and scaling issues (e.g. the transition from static-dynamic frictional behaviour requires special treatment).
  - Hybrid algorithms for different physical processes to be jointly and efficiently simulated (e.g. solid-fluid interactions, heat/dynamical/chemical effects).
  - Common elements such as table look-up and neighbour location algorithms.
- For macroscopic simulation and hybrid simulation (microscopic-macroscopic):
  - Numerical integration algorithms (finite-differences, pseudo-spectral, integral methods, finite-elements, spectral elements, etc.).

2.4 Data Assimilation Working Group (WG4)

The Data Assimilation Working Group will couple closely with the Simulation Models Working Groups (WG1-3), providing constraints for the simulation models. This Working Group will compare the theoretical forecasts to data observations and use these comparisons as a basis to gain insight into the earthquake cycle and earthquake behaviour. This process will provide critical feedback to the Simulation Models Working Groups needed for the model refinement process. Data may include "real time data" and "static data". Static data may conceptually be considered as a fixed database containing all relevant data observations to date whereas real-time data represents the current in-flowing data stream.

2.4.1 Data base and statistical analysis (for condensing information)

Key data types:

- Seismicity (in all tectonic settings: subduction/transcurrent/intraplate),
- Laboratory/rock physics experiment observations,
- Crustal deformation/GPS data,
- Geoelastomagnetic data,
- Electro-magnetic emissions,
- Groundwater observations,
- Earth structure (e.g. detailed or statistical representations of faults, fault systems, plate boundaries, subsurface structure and surface topography).

2.4.2 Inversion analysis (for extracting information)

- Crustal deformation data → seismic and aseismic fault slip
- Seismic activity data → change in stress state
- Seismic waveforms → dynamic rupture processes

2.4.3 Assimilation of real time data (for forecasting)

- Long-term and short-term crustal deformation
- Spatio-temporal change of seismic activity pattern
- Occurance of large earthquakes

2.5 Models Applications Working Group (WG5)

The numerical simulation models developed by ACES for the earthquake cycle in the Asia-Pacific region and related physical processes provide a "virtual laboratory" to probe the behaviour of earthquakes, crustal processes and rock-like solids. This offers a new opportunity to gain an understanding of the earthquake nucleation process, precursory phenomena, the earthquake cycle, and the non-linear behaviour of complex solids. The Models Applications Working Group will involve research that aims to make use of the theoretical forecasts of the simulation models to develop new or improved applications or data analysis systems. Key potential applications include:

2.5.1 Earthquake forecasting

- Intermediate term forecasting - for example, weeks to months

  (e.g. of crustal movements prior to great earthquakes or via new data analysis capabilities developed as a result of the simulations yielding improved comprehension of phenomena such as accelerating moment release or the LURR method of China)

- Short term forecasting - for example, days or less

  (e.g. via new data analysis capabilities developed as a result of the simulations yielding improved comprehension of nucleation and short term precursory phenomena)

2.5.2 Hazard quantification

- Intraplate hazard quantification and spatio-temporal seismicity patterns
- Site amplification of seismic waves
- Scenario earthquakes

2.5.3 Industrial

- Engineering ceramics/materials
- Mining safety
- Induced earthquakes: R.I.S., M.I.S. and other (e.g. petroleum industry)
- Geophysical exploration
- Hyrdrocarbon production
- Construction (civil engineering)

2.6 Participants

ACES participants are listed below to illustrate the strengths and complementarities of the participating economies and research groups.

2.6.1 Economies

Participant Economies each have a different regional tectonic setting, focus, and complementary principal WG strengths as summarised below.

Economy:	*Tectonic setting/Principle WG strengths*
• Australia (Originating Economy):	Intraplate/Microscopic Simulation
• China	Intraplate/Models Applications & Data Assimilation
• Japan	Subduction/Macroscopic Simulation & Data Assimilation
• USA	Transcurrent/Macroscopic Simulation & Data Assimilation

2.6.2 Research groups, centres and institutions

Participant research groups have complementary WG strengths as summarised below. The list contains the principal strengths of each group. Further details on institutional affiliations of groups and centres can be found in the ACES proposal and on the home page, http://quakes.earthsciences.uq.edu.au/ACES.

- **Crustal Activity Modelling Group (Japan)**

  Simulation of the earthquake cycle and crustal movements (Section 2.2.1)

  Data assimilation (Section 2.4, diverse data types)

- **Earthquake Generation and Strong Motion Modelling Group (Japan)**

  Simulation of dynamic rupture and wave propagation (Section 2.2.2)

- **Research Organisation for Information Science and Technology (Japan)**

Common tools for super-parallel computer simulation in the macroscopic domain (Section 2.3, common tools and macroscopic aspects)

- **QUAKES (Australia)**

  Microscopic simulation (see Section 2.1)

  Computational methods (Section 2.3, microscopic aspects)

  Models applications - earthquake and industrial (parts of 2.5.1-2.5.2 & Section 2.5.3)

  Macroscopic simulation (parts of Section 2.2.2 and Section 2.2.3)

- **General Earthquake Model Group (USA)**

  Macroscopic simulation, interacting fault systems (e.g. Section 2.2.3)

  Computational methods (e.g. Section 2.3, macroscopic aspects)

  Nonlinearity and scaling (e.g. Section 2.1.2)

- **SCEC (USA)**

  Data assimilation (e.g. Section 2.4, diverse data types)

  Models applications - hazard quantification (Section 2.5.2)

  Multi-disciplinary approach and physics of earthquakes (e.g. parts of Section 2.1.2 and Sections 2.2.2 and 2.2.3)

- **Nevada Seismological Laboratory (USA)**

  Data assimilation (e.g. Section 2.4, seismicity and laboratory focus)

  Models applications (e.g. application of 2.1.1 and Section 2.5.2)

- **Harvard University Earthquake Modelling Group (USA)**

  Dynamic rupture modelling/macroscopic simulation (e.g. Sections 2.2.1 and 2.2.2)

- **Centre for Nonlinear Earth Systems, LDEO (USA)**

  Macroscopic simulation (e.g. Section 2.2.1)

  Microscopic simulation (parts of Section 2.1)

  Data assimilation (e.g. Section 2.4, laboratory focus)

- **Laboratory for Nonlinear Mechanics (China)**

  Data assimilation (Section 2.4, laboratory/nonlinear mechanics focus)

  Non-linear system/microscopic simulation (meso-mechanics, damage evolution - e.g. Section 2.1.2)

- **Centre for Analysis and Prediction (China)**

  Models applications - particularly earthquake forecasting (Section 2.5.1)

  Data assimilation (Section 2.4, diverse data types)

  Macroscopic simulation (parts of Sections 2.2.2 and 2.2.3)

3. Program of activities

The following activities will be organised. It is anticipated that this list will be expanded and detailed during the ramp-up phase of ACES' activities.

- Annual Workshops:
  - An annual workshop (1 week) will be organised.
  - The first workshop will be held in Brisbane, tentatively on Feb. 1-5, 1999.
  - Subsequent workshops will be rotated amongst Participant Economies.
- Annual Report:
  - An annual progress report will be produced consisting of a compilation of research papers and technical reports of ACES participants.
- Annual Symposium:
  - A one day symposium will be organised during a major international conference (e.g. AGU Fall Meeting, IASPEI or IUGG).
  - It is anticipated that the symposia will alternate between the Fall AGU Meeting and the other major conferences.
- Ongoing Visitors Programs:
  - Visitors programs will be organised between the participant groups and to the ACES Headquarters.
- Target and goal related activities:
  - Target and goal related activities will be undertaken by the Working Groups (e.g. activities aimed at comparing between different numerical solutions, or simulating and developing an understanding of specific phenomena, etc.). These will be developed prior to and during the first ACES Workshop.
- Publicity and outreach activities:
  - Publicity and outreach activities will be developed, largely through the ACES Headquarters.
- Fundraising and infrastructure development:
  - Fundraising and infrastructure development activities will be undertaken by the ACES Headquarters and participant groups.
- Education:
  - 1 summer school per two years is envisaged.

4. Development of by-laws

Draft By-Laws were developed (Attachment 1). These will be used as "working by-laws" until formal endorsement is confirmed according to the following process:

1. Feedback requested from the relevant governmental agencies of Founding Economies.
2. Incorporation of changes after consultation with all ISB members.
3. Iterate on steps 1 and 2 until consensus achieved.
4. Confirmation of endorsement received in writing from Founding Economies.
5. Signing ceremony at inauguration event (probably at the October 1998 APEC Ministers Meeting).

5. Nomination of Executive Director

ISB members from China and Japan submitted nominations for Executive Director of Associate Professor Peter Mora. No other nominations were received. By unanimous vote of ISB members in attendance, Associate Professor Peter Mora was elected as Executive Director of ACES.

6. Organisational and operating framework

The management structure of ACES was specified in the APEC proposal endorsed in Singapore on October 1, 1997 (see Section 1.4 and Appendix A of the APEC proposal). This management structure provides the organisational and operating framework for ACES (see also Section 5 of the APEC proposal). Further discussions were held during the inaugural ISB meeting to elaborate on this framework such that operations could commence. This resulted in the draft By-Laws and the following summary description of the roles of the Executive Office.

6.1 Roles and operation of the Executive Office

The Executive Office will act as ACES Headquarters. The role of the ACES Executive Office is to coordinate ACES activities and act as a central point for scientific interchange via a Visitors Program. Activities include: workshops, annual reports, symposia, summer schools, education, publicity/outreach, target/goal-related activities and fundraising to extend pooled resources (e.g. via sponsorship of ACES from industry or via funding by international or other organisations and agencies). Section 3 provides a complete list of activities that will be coordinated by the ACES Executive Office. The ACES Executive Office will operate through a combination of pooled resources and funding for specific events such as Workshops obtained by the ACES Headquarters and Participants.

7. Identification of ongoing funding requirements and resources

Some issues relating to this agenda item were discussed. However, the time available during the inaugural ISB meeting was insufficient for conclusions to be drawn and recommendations formulated.

Conclusion

Agenda items were addressed during the inaugural meeting of the ACES International Science Board that allow the Cooperation to commence. In accordance with the ISB meeting outcomes, steps have been taken to establish the Executive Office at The University of Queensland and organisation of ACES activities by the Executive Office has commenced.

Attachment 1

Draft By-Laws for ACES

(4 pages)

To be used as working By-Laws until formal endorsement is confirmed.

APEC COOPERATION FOR EARTHQUAKE SIMULATION (ACES)

DRAFT BY-LAWS

ARTICLE I

Name

Section 1, The name of The Cooperation is the APEC Cooperation for Earthquake Simulation (ACES).

ARTICLE II

Participant Economies

Section 1, Founding Economies: The founding economies are:

Australia (Originating Economy)

China

Japan

USA

Section 2, Participant Economies: ACES is open to participation by any APEC Member Economy. Countries or Economies that are not APEC members may join as a Participant Economy subject to endorsement by a majority vote of the nominated representatives of the Participant APEC Economies. Non-APEC Participant Economies will have the same rights as APEC Member Economies except that they may not hold the office of Executive Director.

Section 3, Process to join ACES as Participant Economy: Economies or countries that wish to join ACES as a Participant Economy must express their wish in writing to the International Science Board through the Executive Director, and agree to comply with the By-Laws and any related understandings between the relevant government agencies.

Section 4, Executive Office: The Executive Office will act as ACES Headquarters and play the role of coordinating ACES activities and act as a central point for scientific interchange via a Visitors Program. The Executive Office will operate through a combination of pooled resources obtained from Participant Economy contributions, funding for specific events and activities supplied by ACES participants, and other funds raised by the Executive Office.

ARTICLE III

International Science Board

Section 1, Powers: Full power to specify the science plan and program of activities of ACES shall be vested in the International Science Board (ISB). To this end, the ISB shall have power to authorize such action on behalf of ACES, make rules or regulations for its management, create offices or committees and select, employ or remove such of its officers, agents, or employees as it shall deem best. The ISB shall have the power to fill vacancies in, and change the membership of, such committees as are constituted by it.

Section 2, Composition: The ISB shall be composed of one nominated representative from each Participant Economy.

Section 3, Term of Office: Each member of the ISB shall continue in office until a successor is chosen and qualifies; or until he/she dies, resigns, or is replaced by the relevant agency of the Participant Economy.

Section 4, Resignation: Any ISB Member may resign at any time. Such resignation shall take effect at the time of receipt of the notice by the Chairperson of the ISB and shall specify an interim successor to fill the vacancy until a new nomination is received from the relevant agency of the Participant Economy by the Chairperson of the ISB. The Chairperson shall request a new nomination upon receipt of written notification of resignation.

Section 5, Alternate Representatives: Participating Economies shall nominate alternates for their representative on the ISB to act as a replacement in the event of sickness, death or any other event that prevents the nominated ISB member from fulfilling their duties. Alternates have all the powers of an ISB member unless otherwise specified in the written notification of alternate representation.

ARTICLE IV

Meetings of the International Science Board

Section 1, Annual Meeting: One meeting of the ISB is to be held each year, normally in conjunction with an Annual Workshop, Symposium or other ACES scientific event.

Section 2, Special Meetings: Special Meetings can be called by the Executive

Director.

Section 3, Quorum: The ISB may not make decisions without a quorum of the ISB, deemed as a 2/3 majority attendance of the nominated ISB representatives. Participation in an ISB meeting via video or teleconference links by an ISB member is deemed as attendance for the purposes of the quorum.

Section 4, Voting: Each ISB member will have one vote. Except where otherwise specified by these By-Laws, all matters shall be decided by affirmative vote of a majority of the ISB present at the time of vote, if a quorum is present. In the event of a voting deadlock, the Chairperson of the ISB will cast a deciding vote.

Section 5, Action Without a Meeting: Any action required or permitted to be taken, by the ISB, Executive Director, or any Committee thereof, may be taken without a meeting, if a 2/3 majority of the ISB consent in writing or e-mail to the adoption to the resolution authorizing the action. The resolution and written consents shall be filed with the minutes of the subsequent meeting of the ISB.

ARTICLE V

Offices

Section 1, Offices: The offices of ACES shall consist of an Executive Director who shall serve as Chairperson of the International Science Board, and a Deputy Chairperson or such other offices appointed by the ISB or Executive Director.

Section 2, Executive Director and Chairperson: The Executive Director will call and conduct International Science Board meetings and shall have responsibility for the science program and the budget of ACES. The Executive Director oversees development and implementation of the science plan for ACES in consultation with the other ISB members. The Executive Director will manage ACES activities. The Executive Director, in close consultation with the Board, will take the leadership role in the development of ACES initiatives.

Section 3, Deputy Chairperson: The ISB shall select a Deputy Chairperson from within its members. The Deputy Chairperson will fulfill the role of Chairperson of the ISB in the absence of the Executive Director.

Section 4, Election and Term in Office: The Executive Director will be elected by a majority vote of the ISB for a fixed term of office. The term for the founding Executive Director shall be until 31 December 2001. Subsequent terms shall be three years in duration. At an annual ISB meeting not less than 3 months before the expiration of the fixed term, the ISB will vote on whether to reappoint the Executive Director. A decision not to reappoint the Executive Director would require a 2/3 majority vote. In this event, a new Executive Director will be elected by procedures specified in these By-Laws.

Section 5, Resignation: The Executive Director may resign at any time. Such resignation shall take effect at the time of receipt of the notice by the Deputy Chairperson of the ISB. In this event, the duties and powers vested in the Executive Director shall pass to the Deputy Chairperson who shall ensure that an election for new Executive Director be held within 3 months.

Section 6, Other Offices: The ISB has the power to establish additional offices in accordance with these By-Laws. In this event, such additional offices may be removed by an affirmative vote of the ISB. Offices may also be established by the

Executive Director in order to carry out his/her functions, and implement the science plan and program of activities specified by the ISB. In this case, such offices may be removed at the discretion of the Executive Director. Records must be filed of any offices established or removed by the Executive Director during the subsequent ISB meeting.

ARTICLE VI

Committees, Workings Groups and Advisory Board

Section 1, Establishment of Committees and Standing Committees: The ISB may establish Committees or Standing Committees for specified terms or without time limit. Actions by the ISB to create such Committees shall specify the scope, functions and powers of each Committee and method of appointment of Committee members. Committees may not set policy or take binding action or publish documents without the consent of the ISB. Committees may not create or appoint Sub-Committees without the consent of the ISB.

Section 2, Ad-Hoc Committees and Panels: The Executive Director may appoint Ad-Hoc Committees or Panels to assist in carrying out the business of ACES. Chairs of these committees or panels will report to the Executive Director.

Section 3, Working Groups: Working Groups will be specified by the ISB to address the major scientific programs of the research plan. Working Groups will consist of researchers of participant groups, centres or institutions of the Participant Economies.

Section 4, Advisory Board: The Executive Director, in consultation with the

ISB, may establish an Advisory Board.

ARTICLE VII

Amendment

Section 1, Amendments: These By-Laws may be amended by the affirmative vote of the ISB at any annual or special meeting, the notice, or waiver of notice, of which shall specify the proposed amendment.