Source Sismique: Physique et Perspective pour l'Aléa

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Habilitation à Diriger des Recherches

Université Paris VII - Paris Diderot

Source Sismique: Physique et Perspective pour Aléa

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BRGM, France

devra être soutenu le 13 mai 2009

devant le jury composé de

M. Pascal Bernard (Physicien IPGP)	Rapporteur
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Résumé

Ce rapport résume mes travaux de recherche et présente un plan de perspective. Le titre est intitulé "Processus Dynamique de la Génération de Tremblement de Terre et son Implication vers l'Aléa Sismique" (Dynamic Earthquake Generation Process and its Implication towards to Seismic Hazard). Les travaux ont été réalisés essentiellement à l'Université de Tokyo, Japon (1995 —- 2000), à l'Ecole Normale Supérieure de Paris, France (2000 — 2003), à l'Institut de Radioprotection et de Sûreté Nucléaire, France (2003 — 2004) et au BRGM (French Geological Survey, 2004 — présent) au travers des différentes collaborations. Les recherches focalisent sur les deux centres d'intérêt suivants :

- Comment se passe-t-il un tremblement de terre, notamment au niveau de la source ?
- Comment contribuer au mieux au besoin du risque sismique ?

Pour atteindre ces buts, j'ai concentré mes recherches sur l'approche numérique et théorique, la méthodologie ainsi que la compréhension de la physique des phénomènes et l'application vers l'aléa sismique. Le résultat principal obtenu est la modélisation numérique de la rupture dynamique dans un système complexe de faille lors d'un séisme, par exemple le séisme de Landers en 1992, le séisme d'Izmit en 1999 etc. Il est démontré que ce processus dynamique contrôlé par la contrainte et le comportement de faille affecte le rayonnement des ondes sismique. L'effet de cette source dynamique est donc essentiel pour le mouvement sismique notamment en champ proche de source. Certains aspects de tremblements de terre peuvent être physiquement reproduits, c'est-à-dire, prédictibles. Cette prédictibilité ou non-prédictibilité sera le cœur de ma future recherche.

Table des matières

Chapitre 1

Information Personnelle (Personal Information)

1.1 Curriculum Vitae

AOCHI, Hideo
Né le 7 août 1972 à Tokyo, Japon
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BRGM (French Geological Survey)
Service Aménagement et Risques Naturels (Land Planning and Natural Risk Division)
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Formation

- Doctorat en Science, Department of Earth and Planetary Physics, The University of Tokyo, Japan, “Theoretical studies on dynamic rupture propagation along a 3D non-planar fault system” sous la direction de le Professeur Mitsuhiro Matsu’ura et le Dr. Eiichi Fukuyama, avril 1997 – mars 2000.
- Master en Science, Department of Earth and Planetary Physics, The University of Tokyo, Japan, “Slip- and time-dependent fault constitutive law and earthquake rupture process” sous la direction de le Professeur Mitsuhiro Matsu’ura, avril 1995 – mars 1997.

– Bachelor en Science, Department of Astronomy and Geophysics, Tohoku University, Japan, "Multi-fractal analysis on spatial pattern of seismicity" sous la direction de les Professors Masakazu Ohtake et Haruo Sato, avril 1991 – mars 1995.

Expériences professionnelles

– **Ingénieur expérimenté (Senior Research Scientist) : Service Amenagement et Risques Naturels, BRGM, France, janvier 2008 – présent.**
– **Chef de projet (Project Leader) : Service Amenagement et Risques Naturels, BRGM, France, janvier 2005 – présent.**
– Ingénieur confirmé (Research Scientist) : Service Amenagement et Risques Naturels, BRGM, France, septembre 2004 — décembre 2007.
– Chercheur postdoctoral : Bureau d'Evaluation du Risques Sismiques des Installations Nucléaires, Institute de Radioprotection et de Sûreté Nucleaire, France, février 2003 – septembre 2004 (contrat IRSN).
– Chercheur postdoctoral : Laboratoire de Géologie, Ecole Normale Supérieure Paris, France, avril 2000 — mars 2002 (bourse japonaise JSPS), avril – juillet 2002 (contrat CNRS), octobre 2002 – janvier 2003 (contrat ENS).
– Assistant de recherche (Assistant Staff) en temps partial, The University of Tokyo, Japan, octobre 1998 – mars 2000.
– Assistant d'enseignement (Teaching Assistant) en temps partial, The University of Tokyo, Japan, avril 1997 – septembre 1997.

Expériences invitées

– Chercheur invité (Invited Researcher) : Earthquake Research Institute, The University of Tokyo, Japan, janvier -– février 2003, février 2006, octobre 2007.
– Chercheur invité : Institute for Crustal Study, University of California Santa Barbara, USA, août 2002 – septembre 2002.

Prix, Distinction

– Prix pour jeune sismologue, Seismological Soceity of Japan, mai 2007.
– Postdoctral fellowships for research abroad, Japan Society for the Promotion of Science (JSPS), avril 2000 – mars 2002.

Enseignement

- Sismologie (for undergraduate students), Ecole Normale Supérieure Paris, France, 2002.
- Calcul scientifique (for undergraduate students), The University of Tokyo, Japan, 1995.

Autres expériences

- Jury de thèses : V. Cruz-Atienza, Rupture Dynamique des Failles Non-Planaires en Différences Finies, Université Nice-Sofia-Antipolis, mai 2006 (examinateur). F. Semmane, Charactérisation de la source sismique à partir des données en champs proche. Application aux séismes de Tottori (Japon) et Boumerdes (Algérie), Université Joseph-Fourier, mai 2005 (examinateur).
- Evaluation de propositions de recherche (NSF, ANR)
- Membre de Seismological Society of Japan (depuis 1995), Americal Geophysical Union (depuis 1997), European Geoscience Union (depuis 2000), Association Française de Génie Parasismique (depuis 2005).

Participation aux projets à cofinancement (Financed Project Participations) (extrait)

- "Liens entre complexité de la faille, essaimage de la sismicité et vitesse de rupture : l'importance de l'étude de la Faille Nord Anatolienne (SUPNAF)", coordonné par le Dr. Jean Schmittbul, financé par Agence Nationale de Recherche (programme Risques Naturels), France, 2009 – 2011.
- "DEvelopment of Broadband Acceleration Time histories for engineers (DEBATE)", coordonée par Hideo Aochi, financé par Agence Nationale de Recherche (programme Risques Naturels), France, 2009 — 2011.
- "Rhéologie des Aspérités de Faille : Rôle des Fluides - Intégration à l'Echelle du Cycle Sismique", coordonné par Dr. Renaud Toussaints, financé par Institute National des Sciences de l'Universe, France, 2007.
- "Adaptation et optimisation des performances applicatives sur architectures NUMA : Etude et mise en oeuvre sur des application en sismologie (NUMASIS)", coordonné par Dr. Jean Francois Mehaut, financé par Agence Nationale de Recherche (programme Calcul Intensif), France, 2006 – 2008.
- "Quantitative Seismic Hazard Analysis (QSHA)", coordonné par le Professor Jean Virieux, financé par Agence Nationale de Recherche (programme Catastrophes Telluriques et Tsunamis), France, 2006 – 2008.
- "Seismic simulation in complex source-site context (SEISMULATORS)", coordonnée par Hi-

deo Aochi, finance par Agence Nationale de Recherche (programme Catastrophes Telluriques et Tsunamis), France, 2006 – 2008.

– “Special Project for Earthquake Disaster Mitigation in Urban Area (Dai-Dai-Toku)” financé par Ministry of Education, Culture, Sports, Science and Technology, Japan, 2002 – 2007.
– “How Can We Improve Ground Motion Estimates by Lessons Learned From Rupture Dynamics ?” coordonné par Dr. Kim Olsen, finance par Southern California Earthquake Center, USA, 2002 – 2007.
– “APEC Cooperation for Earthquake Simulation (ACES)” financé par Australia, China, Japan and USA, 1999 – 2004.
– “3D modeling of crustal deformation and tectonic stress loading process around Japan” coordonné par le Professor Mitsuhiro Matsu’ura, finance par Minstry of Education, Japan, 1995 – 1997.

Organisation

– Convener de la session “Dynamic earthquake rupturing at various scale”, American Geophysical Union Fall Meeting, San Francisco, décembre 2008.
– Chairman de la session “Characterisation des mouvements forts”, the 7th national colloquium of the Asssociation Francaise de Genie Parasismique, Chatenay-Malabry, France, juillet 2007.
– Co-convener de la session “Fault zone properties and behaviors in earthquakes”, Western Pacific Geophysics Meeting of AGU, Beijing, China, juillet 2006.
– Co-organizer of the international joint workshop “New Trends in Seismic Vulnerability and Risk Assessment” with the Kobe University, Orléans, France, décembre 2005.

1.2 Encadrement (Research Coordination)

En tant que chef de projet dans un organisme publique, les expériences d'encadrement aquises sont essentiellement la coordination de projets et le management des équipes d'ingénieurs.

Encadrement d'étudiants et de postdocs

- Florent De Martin (BRGM), collaboration dans le cadre de sa thèse sur le couplage des simulations de la propagation des ondes en différence finie et de l'effet nonlinéaire du sol en éléments finis (directeur : Professeurs Arezou Modaressi et Hiroshi Kawase), 2007 – 2009.
- Fabrice Dupros (BRGM), collaboration dans le cadre de sa thèse sur l'optimisation du code en différence finie (directeur : Professeurs Jean Roman et Dimitri Komatitsch), 2007 – 2009.
- Jerôme Salichon (BRGM), CDD sur l'étude du séisme des Saintes en 2004 en Antilles, 2006 – 2007.
- Victor Cruz-Antienza (Université de Nice-Sophia-Antipolis), collaboration dans le cadre de sa thèse sur la comparaison des méthodes entre les équations intégrales et les différences finies (directeur : Professeur Jean Virieux), 2004 – 2006.
- Plusieurs (co-)encadrements de stagiaires (master, école ingénieur).

Coordination de projets

- **Coordination de projet national "DEvelopment of Broadband Acceleration Time histories for Engineers (DEBATE)" (BRGM, ENS Paris, IRSN, Géodynamique & Structure), Agence Nationale de Recherche (programme Risques Naturels), France, 2009 — 2011.**
- **Coordination de projet national "SEISmic siMULATion of complex sOuRce-Site context (SEISMULATORS)" (BRGM, IPGP, ENS Paris, ECP, IRSN), Agence Nationale de Recherche (program Catastrophes Telluriques et Tsunamis), France, 2006 – 2008. (http ://seismulators.brgm.fr)**
- **Chef de projet cadre "Risques sismiques", BRGM, France, 2005 – présent.**
  - **Coordination de l'ensemble de projets en cours au BRGM sur la thématique. (7 projets sous contrat externe en fin 2008)**
  - **Coordination des actions internes de recherche sur la thématique. (4,5 personne.an sur l'année 2008)**
- Project fellow "Theoretical study on rupture processes of interacting complex fault systems", Japan Society for the Promotion of Science, Japan, 2000 – 2002.

1.3 Liste de Publication (Publication List)

updated on 31 December 2008.

Theses

1. Aochi, H., Theoretical studies on dynamic rupture propagation along a 3D non-planar fault system, PhD thesis, University of Tokyo, Japan, March 2000.
2. Aochi, H., Slip- and time-dependent fault constitutive law and earthquake rupture process, Master thesis, University of Tokyo, Japan, March 1997 (in Japanese).

Book

1. Uenishi, K., N. Kame and H. Aochi, Seismology - Quantitative Approach - (Translation of "Quantitative Seismology Second Edition" by K. Aki and P. G. Richards), pp.909, Kokin Shoin, Tokyo, Japan, 2004 (in Japanese).

Papers in refereed journals

1. Aochi, H. and S. Ide, Complexity in earthquake sequences controlled by multi-scale heterogeneity in fault fracture energy, *in press, J. Geophys. Res.*, 2008.
2. Aochi, H. and R. Ando, Numerical simulations on faulting : Microscopic evolution, macroscopic interaction and rupture process of earthquakes, *in press, J. Seism. Soc. Japan*, 2008.
3. Douglas, J. and H. Aochi, A survey of techniques for predicting earthquake ground motions for engineering purposes, *Surv. Geophys.*, **29**, 187–220, 2008.
4. de Michele, M. D. Racoules, H. Aochi, N. Baghadadi and C. Carnec, Measuring coseismic deformation on the northern segment of the Ban-Baravat escarpment associated with the 2003 Bam (Iran) earthquake, by correlation of very-high-resolution satellite imagery, *Geophys. J. Int.*, **173**, 459–464, 2008.
5. Cruz-Atienza, V., J. Virieux and H. Aochi, 3D Finite-Difference Dynamic-Rupture Modelling Along Non-Planar Fault, *Geophysics*, **72**(5), SM123–SM137, 2007.
6. Douglas, J., H. Aochi, P. Suhadolc and G. Costa, The importance of crustal structure in explaining the observed uncertainties in ground motion estimation, *Bull. Earthq. Engineering*, **5**, 17–26, 2007.
7. Aochi, H. and J. Douglas, Testing the validity of simulated strong ground motion from the dynamic rupture of a fault system, by using empirical equations, *Bull. Earthq. Engineering*, **4**, 211–229, 2006.

8. Aochi, H., M. Cushing, O. Scotti, and C. Berge-Thierry, Estimating rupture scenario likelihood based on dynamic rupture simulations : the example of the segmented Middle Durance fault, southeastern France, *Geophys. J. Int.*,**165**, 436-446, 2006.
9. Ide, S. and H. Aochi, Earthquakes as multiscale dynamic ruptures with heterogeneous fracture surface energy, *J. Geophys. Res.*, *110*, B11303, doi :10.1029/2004JB003591, 2005.
10. Aochi, H., O. Scotti, and C. Berge-Thierry, 3D dynamic rupture propagation along complex segments with different mechanisms, *G*eophys. Res. Lett., **32**, L21304, doi :10.1029/2005GL024158, 2005.
11. Aochi, H. and K. B. Olsen, On the effects of non-planar geometry for blind thrust faults on strong ground motion, *Pure appl. Geophys.*, **161**, 2139-2153, 2004.
12. Aochi, H. and S. Ide, Numerical Study on Multi-Scaling Earthquake Rupture, *Geophys. Res. Lett.*, **31**(2), 10.1029/2003GL018708, 2004.
13. Aochi, H. and R. Madariaga, The 1999 Izmit, Turkey, earthquake : Non-planar fault structure, dynamic rupture process and strong ground motion, *Bull. Seism. Soc. Am.*, **93**, 1249-1266, 2003.
14. Aochi, H. and E. Fukuyama and R. Madariaga, Constraints of Fault Constitutive Parameters Inferred from Non-planar Fault Modeling, *Geichemistry, Geophysics, Geosystems*, **4**(2), 10.1029/2001GC000207, 2003.
15. Aochi, H. and M. Matsu'ura, Slip- and time-dependent fault constitutive law and its significance in earthquake generation cycles, *Pure appl. Geophys.*, **159**, 2029-2044, 2002.
16. Aochi, H., R. Madariaga and E. Fukuyama, Effect of Normal Stress During Rupture Propagation along Non-planar Fault, *J. Geophys. Res.*, **107**(B2), 10.1029/2001JB000500, 2002.
17. Aochi, H. and E. Fukuyama, Three-dimensional nonplanar simulation of the 1992 Landers earthquake, *J. Geophys. Res.*, **107**(B2), 10.1029/2000JB000061, 2002.
18. Aochi, H., E. Fukuyama and M. Matsu'ura, Selectivity of spontaneous rupture propagation on a branched fault, *Geophys. Res. Lett.*, **27**, 3635-3638, 2000b.
19. Aochi, H., E. Fukuyama and M. Matsu'ura, Spontaneous Rupture Propagation on a Non-planar Fault in 3D Elastic Medium, *Pure appl. Geophys.*, **157**, 2003-2027, 2000a.

Proceedings of Conferences

1. Dupros, F., H. Aochi, A. Ducellier, D. Komatitsch, and J. Roman, Exploiting intensive multi-threading for efficient simulation of seismic wave propagation, 11th International Conference on Computational Science and Engineering, San Paulo, Brazil, July 2008.

2. De Martin, F., H. Aochi and H. Modaressi, Reponse dynamique d'une vallee alpine sous excitation sismique, 7eme Colloque National AFPS, A093, Chatenay-Malbrey, France, July 2007.

3. De Martin, F., H. Modaressi, and H. Aochi, Coupling of FDM and FEM in seismic wave propagation, 4th international conference on Earthquake Geotechnical Engineering, Paper No. 1743, Thessaloniki, Greece, June 2007.

4. Bernardie, S., H. Aochi, H. Modaressi and R. Madariaga, Some Insights on Dynamic Rupture Modelling Using a Finite Element Method, 1st European Conference on Earthquake Engineering and Seismology, Geneva, Switzerland, September 2006.

5. Douglas, J., H. Aochi, P. Suhadolc and G. Costa, On the applicability of one-dimensional crustal structures for ground-motion simulation, 1st European Conference on Earthquake Engineering and Seismology, Geneva, Switzerland, September 2006.

6. Aochi, H., J. Rey and J. Douglas, Numerical Simulation of Wave Propagation in the Grenoble Basin : Benchmark ESG2006, 3me International Symposium on the Effects of Surface Geology on Seismic Motion, Grenoble, France, August 2006.

7. Douglas, J., H. Aochi, P. Suhadolc, G. Costa, The importance of crustal structure in explaining the observed uncertainties in ground motion estimation, International Conference on Earthquake Engineering in 21 Centrury, Skopje, Macedonia, August 2005.

8. Aochi, H., E. Durukal and L. F. Bonilla, Assessment of Lateral Spreading : Modeling a Case from the 1999 Kocaeli, Turkey Earthquake, the 11th International Conference on Soil Dynamics and Earthquake Engineering and the 3rd International Conference on Earthquake Geotechnical Engineering, Berkeley, USA, January 2004.

9. Aochi, H. and E. Fukuyama, Scrutiny of the 3-D non-planar fault model of the 1992 Landers earthquake, in Proceedings of the 2nd ACES Workshop, edited by M. Matsu'ura, K. Nakajima and P. Mora, 335-341, 2001.

10. Olsen, K. B., E. Fukuyama, H. Aochi and R. Madariaga, Hybrid modeling of curved fault radiation in a 3D heterogeneous medium, in Proceedings of the 2nd ACES Workshop, edited by M. Matsu'ura, K. Nakajima and P. Mora, 343-349, 2001.

11. Aochi, H., and M. Matsu'ura, Evolution of contacting rock surfaces and a slip- and time-dependent fault constitutive law, in APEC Cooperation for Earthquake Simulation (ACES), 1st ACES Workshop Proceedings, edited by P. Mora, 135-140, 1999.

12. Hirata, N., T. Iwasaki, H. Aochi and M. Matsu'ura, Modeling of plate boundaries and intra-arc active fault systems in and around Japanese islands, in APEC Cooperation for Earthquake Simulation (ACES), 1st ACES Workshop Proceedings, edited by P. Mora, 171-175, 1999.

13. Aochi, H., E. Fukuyama and M. Matsu'ura, An expression of stress field in 3D elastic medium using boundary integral equation method, in APEC Cooperation for Earthquake Simulation (ACES), 1st ACES Workshop Proceedings, edited by P. Mora, 239-245, 1999.

Abstracts in conference proceedings (selected)

1. De Michel, M., . Raucoules, J. Salichon, A. Lemoine and H. Aochi, Mapping deformation field prior to an earthuake : InSAR observations 1993-2004 before the Mw6.0 Parkfield event, Eos Trans, AGU, 89(53), Fall Meet. Suppl., Abstract S21B-1816, San Francisco, USA, December 2008.
2. Raucoules, D., M. De Michel, H. Aochi and C. Carnec, Mapping the earthquake rupture and displacement field using correlation of ALOS PALSAR amplitude images : Application to the Mw7.9 Sichuan earthquake, 12 May 2008, Eos Trans, AGU, 89(53), Fall Meet. Suppl., Abstract G33C-0703, San Francisco, USA, December 2008.
3. Kame, N. and H. Aochi, A hybrid FDM-BIEM approach for dynamic rupture simulation, Eos Trans, AGU, 89(53), Fall Meet. Suppl., Abstract S51D-1763, San Francisco, USA, December 2008.
4. Poisson, B. and H. Aochi, Effect of fault geometry on earthquake rupture migration induced by fluid injection, Eos Trans, AGU, 89(53), Fall Meet. Suppl., Abstract S51D-1771, San Francisco, USA, December 2008.
5. Aochi, H. and S. Ide, Complexity in earthquake sequences controlled by multi-scale heterogeneity in fault fracture energy, Eos Trans, AGU, 89(53), Fall Meet. Suppl., Abstract S51D-1779, San Francisco, USA, December 2008.
6. Aochi, H. and A. Kato, Three-dimensional non-planar dynamic rupture process of the 2007 Mw6.6 Niigata-ken Chuetsu-Oki, Japan, earthquake, Japan Geoscience Union Meeting, Chiba, May 2008.
7. Kame, N. and H. Aochi, A hybrid FDM-BIEM approach for dynamic rupture simulation : Part II, Japan Geoscience Union Meeting, Chiba, May 2008.
8. Aochi, H. and S. Ide, Multi-scale heterogeneous fault system for dynamic rupture events during a seismic cycle, Seismological Society of Japan Fall Meeting, Sendai, Japan, October 2007.
9. Aochi, H., J. Douglas, S. Ide, Heterogeneous dynamic rupture modeling for strong ground motion simulation, Geophysical Research Abstracts, 9, 05591, Vienna, Austria, 2007.
10. Aochi, H. and S. Ide, Numerical simulation of temporal evolution of multi-scale earthquake rupture, Geophysical Research Abstracts, 9, 05583, Vienna, Austria, 2007.

11. Aochi, H., J. Salichon and A. Lemoine, Validation of teleseismic inversion of the 2004 Les Saintes, Lesser Antilles, earthquake (Mw6.3) from 3D finite-difference forward modelling, Geophysical Research Abstracts, 9, 05465, Vienna, Austria, 2007.
12. Aochi, H., Dynamic rupture modelling along a fault system, Eos Trans, AGU, 87(36), West. Pac. Geophys. Meet. Suppl., Abstract S35A-04, Beijing, China, 2006 (invited).
13. Aochi, H., J. Le-Puth and S. Ide, Attempts at using a dynamic rupture source model for ground-motion simulations, Eos Trans, AGU, 87(36), West. Pac. Geophys. Meet. Suppl., Abstract S11E-0160, Beijing, China, 2006.
14. Jousset, P. and H. Aochi, Regional scale numerical simulation of wave propagation for seismic hazard evaluation study, Geophysical Research Abstracts, 8, 02396, Vienna, Austria, April 2006.
15. Lemoine, A., H. Aochi, G. Bertrand, J. Lambert, C. Lembezat and T. Winter, Source parameters inversion using macroseismic data in a moderately seismic context (France), Geophysical Research Abstracts, 8, 04454, Vienna, Austria, April 2006.
16. Ide, S. and H. Aochi, Rupture propagation and seismic energy radiation along fault surfaces of fractal characteristics, Eos Trans. AGU, 86 (52), Fall Meet. Suppl., Abstract, S51F-01, 2005.
17. Aochi, H., M. Seyedi, J. Douglas, E. Foerster and H. Modaressi, A complete BIEM-FDM-FEM simulation of an earthquake scenario - dynamic rupture proecss, seismic wave propagation and site effects, Geophysical Research Abstracts (European Geoscienecs Union General Assembly, Vienna, Austria, April), 7, 02589, 2005.
18. Aochi, H. and S. Ide, Numerical simulation of cascade and pre-slip rupture models, Geophysical Research Abstract (European Geosciences Union General Assembly, Vienna, Austria, April 2005), 7, 02602, 2005.
19. Aochi, H., C. Berge-Thierry, E. Cushing, O. Scotti and Ph. Volant, Probabilistic and dynamic approaches of earthquake scenarios in the Moyenne Durance, France, XXIX General Assembly of European Seismological Commission, Potsdam, Germany, September 2004.
20. Ide, S. and H. Aochi, Multiscale dynamic rupture simulation on fractal patch model, Western Pacific Geophysics Meeting, Hawaii, USA, August 2004.
21. Aochi, H., O. Scotti and C. Berge-Thierry, Importance of Intermediate Principal Stress Magnitude in Dynamic Rupture Propagation in 3D, Eos Trans. AGU, 84(47), Fall Meet. Suppl., Abstract S21G-05, 2003.
22. Ide, S. and H. Aochi, Numerical Study on Multi-Scaling Earthquake Rupture, Eos Trans. AGU, 84(47), Fall Meet. Suppl., Abstract S42D-0199, 2003.

23. Berge-Thierry, C., H. Aochi, E. Cushing, O. Scotti and P. Volant, Scenario Earthquake in the Moyenne Durance, South-Eastern France, Eos Trans. AGU, 84(47), Fall Meet. Suppl., Abstract S41C-0104, 2003.
24. Aochi, H. and S. Ide, Numerical Study on Multi-Scaling Earthquake Rupture, Fall Meeting of SSJ, Kyoto, Japan, October 2003 (in Japanese).
25. Aochi, H. and R. Madariaga, Dynamic modeling of the 1999 Izmit, Turkey earthquake on non-planar fault models, Eos Trans. AGU, 83(47), Fall Meet. Suppl., Abstract NG62A-0939, 2002.
26. Olsen, K. B. and H. Aochi, On the effects of non-planar fault geometry on strong ground motion, Eos Trans. AGU, 83(47), Fall Meet. Suppl., Abstract S12B-1209, 2002.
27. Aochi, H. and R. Madariaga, Fault parameters of the 1999 Izmit earthquake inferred from accerelogram near the fault, Geophysical Research Abstracts, 4, 27th General Assembly of the European Geophysical Society, EGS02-A-00618, 2002.
28. Aochi, H., K. B. Olsen, E. Fukuyama and R. Madariaga, Hybrid simulation of dynamic rupture and seismic wave propagation, Geophysical Research Abstracts, 4, 27th General Assembly of the European Geophysical Society, EGS02-A-00619, 2002.
29. Aochi, H. and R. Madariaga, The 1999 Izmit, Turkey, earthquake, Non-planar fault structure, dynamic rupture process and strong ground motion, EOS Trans, American Geophysical Union, 82(47), Fall Meeting Suppl., Abstract S31C-04, 2001.
30. Aochi, H., E. Fukuyama and R. Madariaga, Dynamic rupture modeling with non-planar faults and generation of strong motion, Japan Earth and Planetary Science Joint Meeting, Tokyo, Japan, July 2001.
31. Aochi, H., R. Madariaga and E. Fukuyama, Constraint of fault properties on strong motion based on non-planar fault modeling, Geophysical Research Abstracts, 3, 26th General Assembly of the European Geophysical Society, 911, 2001.
32. Aochi, H., E. Fukuyama and R. Madariaga, Effect of normal stress on a dynamic rupture along non-planar fault, EOS Trans AGU, 81(48), Fall Meeting Suppl., Abstract T21G-02, 2000.
33. Aochi, H., and E. Fukuyama, A New Approach for the Non-Planar Fault Modeling of Dynamic Rupture During the 1992 Landers Earthquake, EOS Trans AGU, 81(22), Western Pacific Geophysics Meeting, S51D-02, 2000.
34. Aochi, H., E. Fukuyama and M. Matsu'ura, 3D Non-planar Simulation of the 1992 Landers Earthquake, 25th General Assembly of EGS, Nice, France, April 2000.
35. Aochi, H., E. Fukuyama and M. Matsu'ura, Dynamics of Rupture Propagation on 3D Complex Faults, EOS Trans AGU, 80(46), Fall Meeting Suppl., S51E-04, 1999.

36. Aochi, H., E. Fukuyama and M. Matsu'ura, Dynamics of Branching Faults, Seismological Society of Japan Fall Meeting, Sendai, Japon, November 1999 (in Japanese).
37. Aochi, H., E. Fukuyama and M. Matsu'ura, Dynamic rupture simulation on a bending fault using 3D BIEM, Japan Earth and Planetary Science Joint Meeting, Tokyo, Japon, June 1999 (in Japanese).
38. Aochi, H., and M. Matsu'ura, 3D-simulation of spontaneous earthquake rupture processes with a slip- and time-dependent constitutive law, AGU Fall Meeting, San Francisco, USA, December 1998.
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Chapitre 2

Introduction Générale (General Introduction)

Je me sens toujours familier avec les termes “tremblements de terre”, même si je n’ai jamais vécu un tel désastre. Pendant ma vingtaine d’années passées au Japon, il y a eu plusieurs séismes destructeurs tels que le Nihon-kai Chubu-oki en 1983, le Nagano-ken Seibu en 1984, le Hyogo-ken Nanbu (Kobe) en 1995 et bien d’autres... Ils sont illustrés dans la Figure 2.1. Dans les années 80, nous avons appris à l’école que le prochain séisme dans la région Tokai (M7.5), sud-ouest de Tokyo, est prédictible. A chaque fois que le gouvernement donne une alerte, les élèves rentrent immédiatement chez eux et se préparent pour le séisme à venir. Seulement 20 ans après, une telle alerte n’a jamais été sonnée et ce séisme n’a pas encore lieu...

La cartographie de l’aléa sismique probabiliste au Japon a été publiée il y a quelques années. Un exemple vous est montré dans la Figure 2.2). L’endroit près de subductions comme la région Tokai est toujours coloré avec une probabilité très élevée d’un mouvement fort même par rapport à la durée de la vie humaine. J’ai compris maintenant qu’il est extrêmement compliqué de prédire un prochain tremblement de terre, car le mécanisme du séisme (processus de génération de séisme) est tellement complexe. A ce jour, nous n’avons pas suffisamment de connaissances ni sur l’intérieur de la Terre, ni sur la mécanique de cette rupture et de sa déformation. Nous ne sommes donc pas capables d’établir le système déterministe pour la prédiction.

Dans la plupart de cas, des séismes ont lieu en profondeur et on ne peut ni observer ni mesurer ces sources directement sur place. Les observations sismologiques et géodésiques sont limitées à la surface de la Terre ou à proximité de la surface. A l’interprétation de ces données, nous obtenons une image de la source sismique. Dans certains cas, nous constatons une trace de source sismique visible sur la surface de la Terre (Figure 2.3), par exemple des grands séismes récents (environ une magnitude 7 ou plus) peu profonds ou des grand séismes très anciens qui montaient en surface suite à la déformation terrestre à long terme. Une de mes premières observations sur terrain était au centre

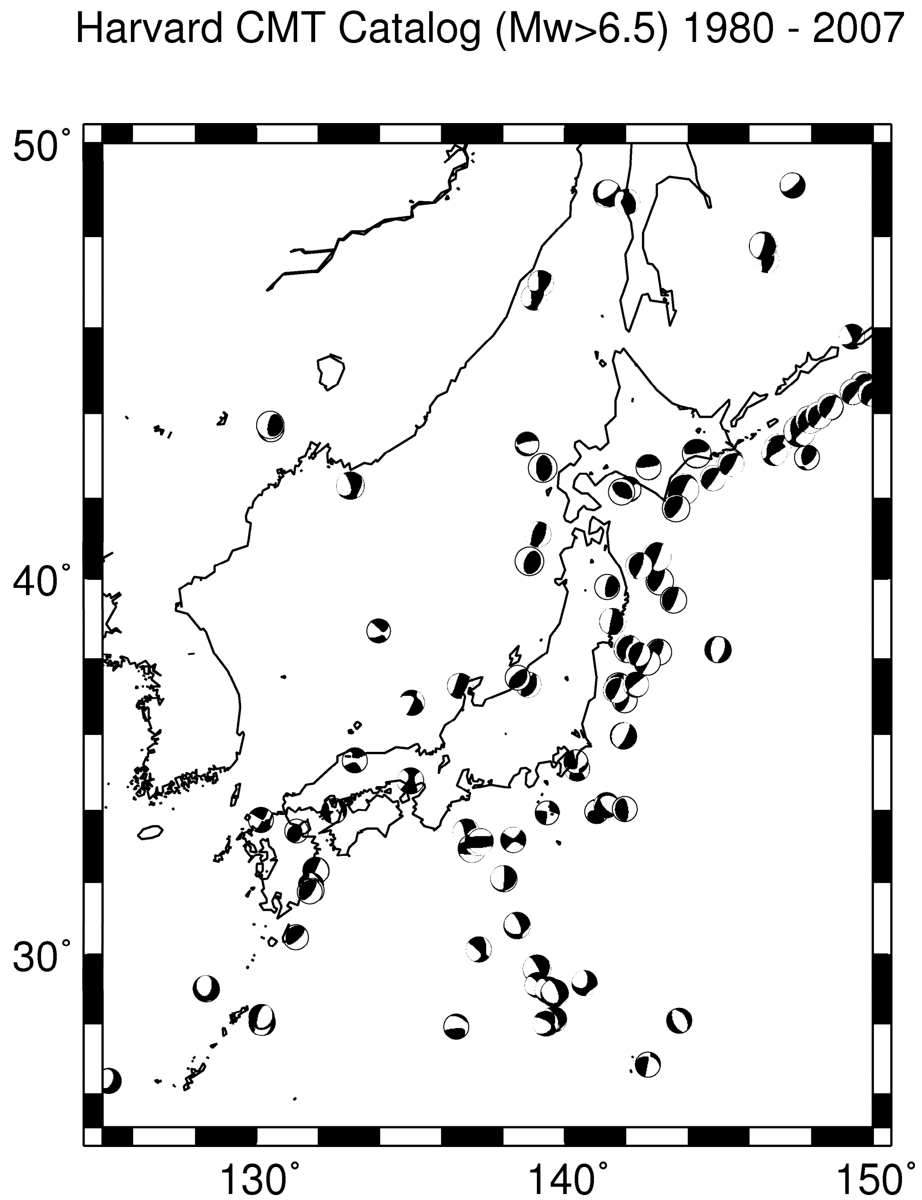


FIGURE 2.1 – Seismicity around Japan (Controid Moment Tensor solutions from the Havard catalog between the year 1980 and 2007, whose moment magnitude M_w are equal or larger than 6.5). As major damaging earthquakes, there occurred the 1983 Nihon-kai Chubu (M7.7), the 1993 Hokkaido Nansei-oki (M7.8), the 1995 Hyogo-ken Nanbu (M7.3), the 2000 Tottori-ken Seibu (M7.3), the 2001 Geiyo (M6.7), the 2003 Kushiro-Oki (M8.0), the 2004 Niigata-ken Chuestu (M6.8), the 2005 Fukuoka-ken Seiho-oki (M7.0), the 2007 Noto-hanto (M6.9), the 2007 Niigata-ken Chuestu-Oki (M6.8) and the 2008 Iwate-Miyagi-Nairiku (M7.2), for example (Japan Meteorological Agency).

du Japon, dans une partie de la zone de faille Itoigawa-Shizuoka où l'aléa sismique est très élevé en direction sud nord (toute la largeur du centre du Japon) dans la Figure 2.2. Les failles (traces de rupture) anciennes ont eu lieu en profondeur et sont montées vers la surface ultérieurement.

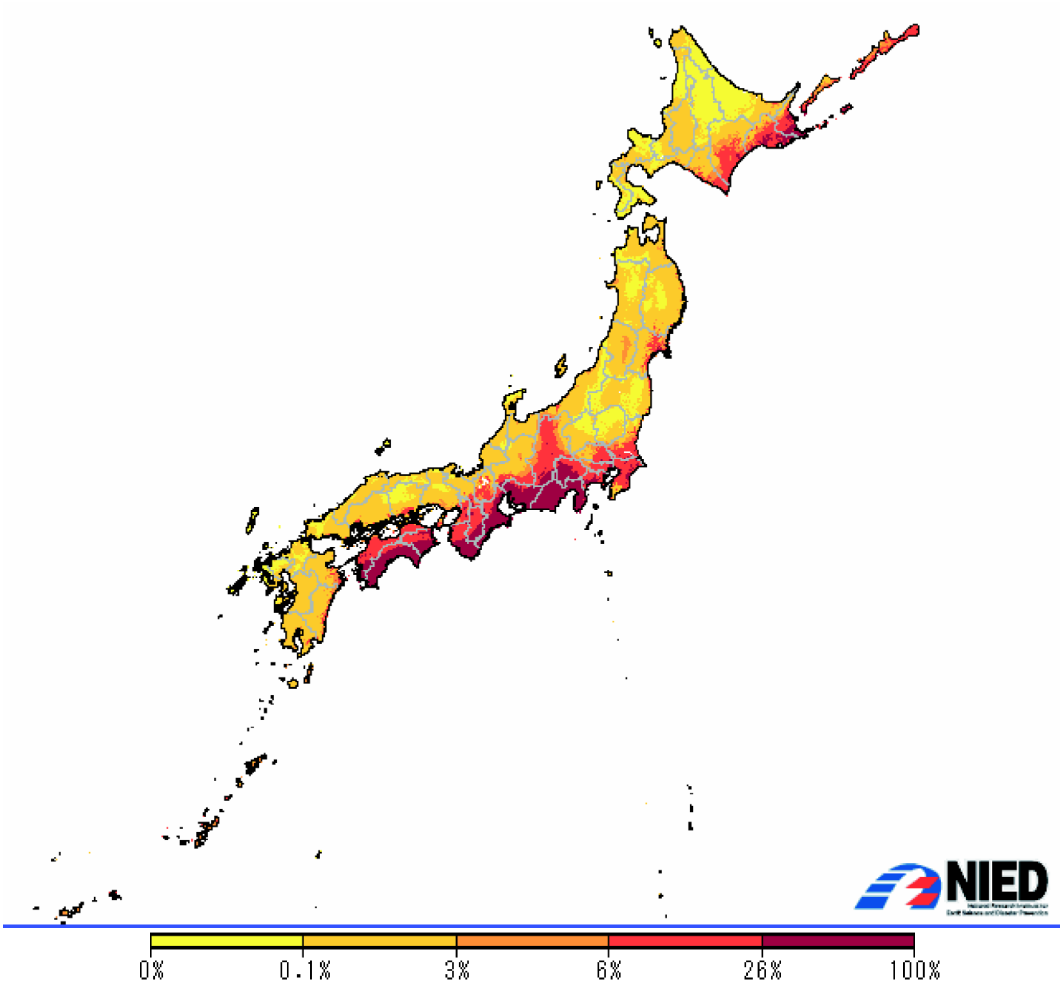


FIGURE 2.2 – National seismic hazard map for Japan (J-SHIS) published by the National Research Institute for Earth Science and Disaster Prevention (NIED). The color scale shows the probability of ground motions equal to or larger than JMA intensity 6 lower within 30 years beginning on the date of January 1, 2007.

Il est impressionnant de voir des traces de rupture (plutôt très fines) et des pseudotachylites qui devaient être générées et déformées par le glissement très rapide lors du séisme. Un géologue m'a expliqué qu'une faille devient très résistante après un séisme (due à cette "pseudotachylité"). Par conséquent, le séisme suivant casse une autre trace. Cette explication concorde avec le modèle de faille présenté dans la Figure 5.4 ? ? J'ai aussi visité la faille San Andreas, une trace du séisme de San Francisco en 1906. La déformation (surtout la discontinuité au travers de faille) est très évident à voir, même pour les amateurs ! Il est étonnant que la déformation soit aussi localisée autour d'une trace claire. Par contre, une autre visite à la faille de Moyenne Durance (sud-est de la France) a nécessité beaucoup de mon imagination afin de figurer comment elle est. Malheureusement jusqu'à présent, je n'ai pas encore eu l'occasion de voir les failles de Landers et d'Izmit, pour lesquelles j'ai

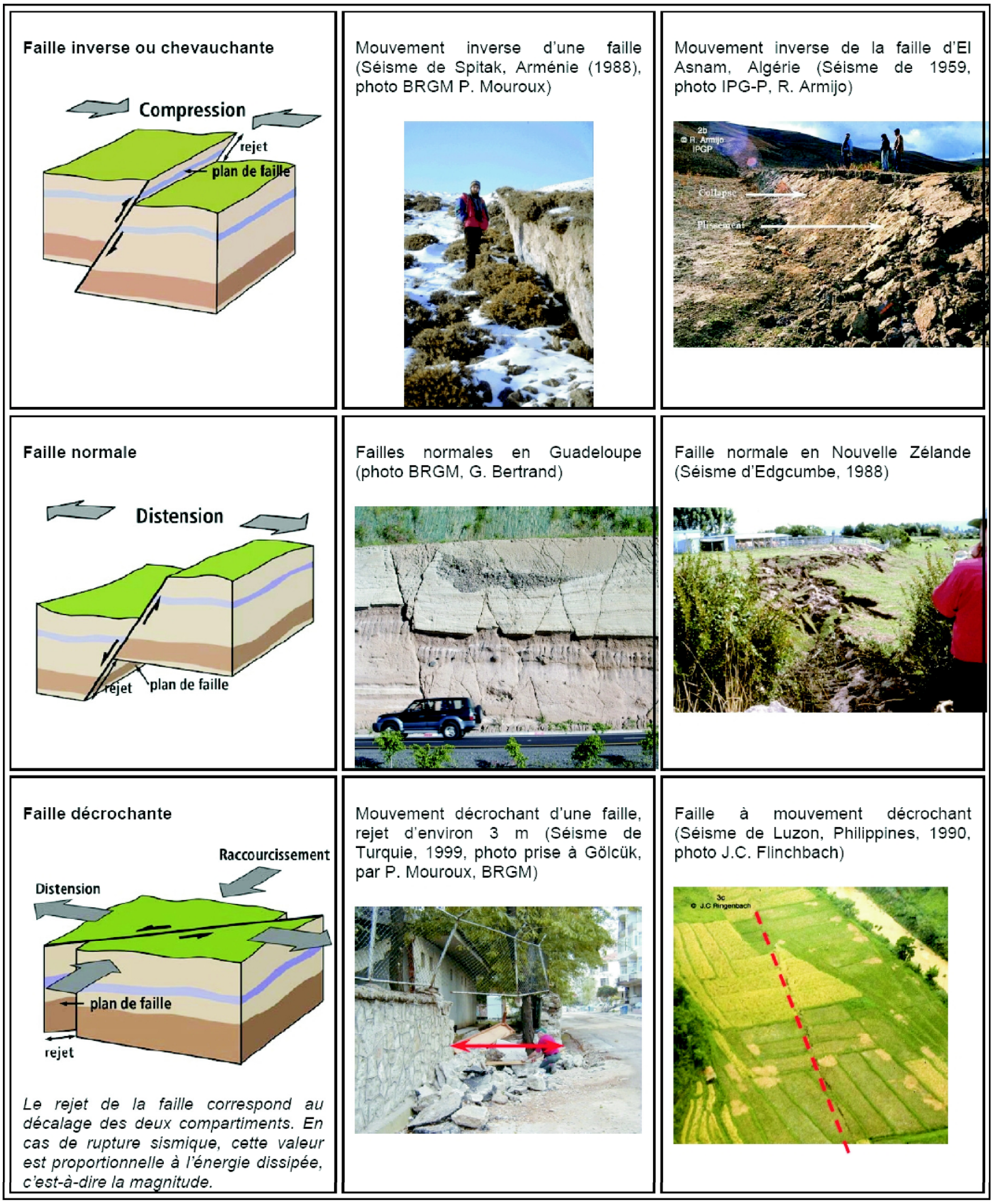


FIGURE 2.3 – Illustration of earthquake faultings (reverse, normal and strike-slip faultings from top to down) with some photos of the faults. After Terrier (2006).

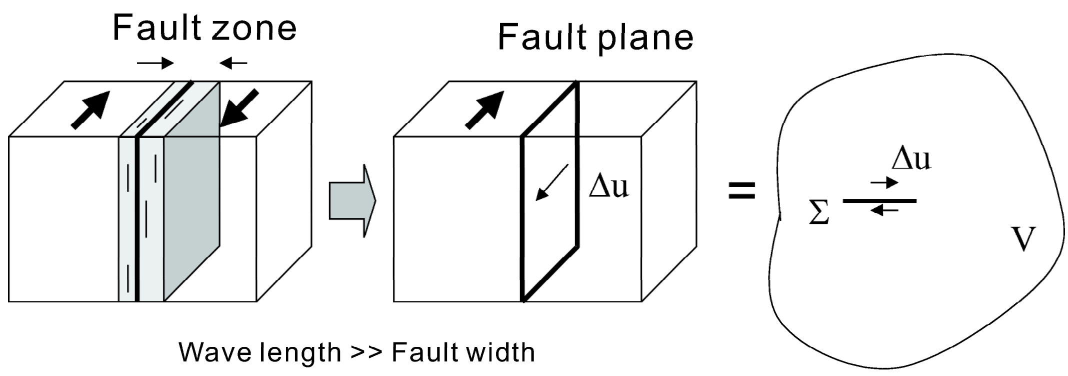


FIGURE 2.4 – Schematic illustration of fault description. Geological fault consists of rheologically complex fault zone including main fracture plane, fracture zone and damaged zone. In seismological description, wavelength of interest is usually much longer than the fault zone so that fault relative movement is mapped as discontinuity along fault plane. This is equivalent to the internal interface problem in an elastic medium.

tellement travaillé en modélisation.

Ainsi le champ où les tremblements de terre ont lieu semble très varié et leur processus semble complexe. Néanmoins dans le cas où l'on envisage de comprendre ces phénomènes par modélisation, il faut simplifier les éléments sans perdre l'essentiel du mécanisme. "Le processus est dominé par la physique". Je voudrais mettre en plus l'accent sur le fait que certains aspects des tremblements de terre sont compréhensibles d'un point de vue physique. Mes activités de recherche le démontrent. Quand nous regardons réellement une faille cassée pendant le séisme, nous savons que le processus de rupture est très complexe. Une interface (discontinuité) est très fine tout au long de la fissure mais la zone de faille se forme avec plusieurs traces de fissure et des rochers fondus et endommagés. Physiquement parlant, les études sismologiques sont souvent limitées à certaine bande d'échelle (longueur d'onde). Par conséquent, la complexité à petite échelle peut être homogénéisée (Figure 2.4). La zone volumétrique de faille est considérable comme une plane de faille et toute la complexité est projetée comme une relation constitutive de faille sur cette interface (comportement de faille). Cette approximation s'accorde bien avec la théorie de représentation en sismologie et en élastodynamique où une interface de fissure (faille) est supposée sans épaisseur dans le milieu élastique et que le comportement non-linéaire concernant cette faille (domaine source) est traduit en forme de mouvement induit le long de l'interface.

On peut diviser ce problème en deux : le premier est de connaître la réponse du milieu, qui est décrit par un système des équations de mouvement en milieu continu bien connues ; le second est de comprendre comment décrire le domaine de source incluant le comportement non-linéaire de la rupture. L'imagerie du mouvement sur la surface de faille lors d'un séisme peut être obtenue par inversion notamment à partir des sismogrammes en base fréquence. Cette optique a eu beaucoup de succès dans la compréhension "cinématique" du rayonnement des ondes par une faille. Cependant les deux aspects mécaniques mentionnés ci-dessus devront être associés afin de mieux comprendre la physique dans ce phénomène de rupture, c'est-à-dire que se passe t-il vraiment le long de la faille pendant un séisme ? Il faut noter ici que le processus de rupture est en fait "spontané" selon certaine loi physique qui contrôle la condition de contrainte et de mouvement sur cette faille et la réponse dynamique du milieu en voisinage. Cette approche focalise sur l'aspect "dynamique" du séisme, pour distinguer de l'aspect "cinématique" (e.g. Aki and Richards, 1980). C'est le cœur de ma recherche, qui constitue un des objectifs principaux de mes travaux depuis ma thèse.

Après l'introduction, le Chapitre 4 vous présente les différentes méthodes numériques que je développe et utilise pour étudier le processus de la rupture dynamique et la propagation des ondes sismiques conséquente. Elles permettent d'approfondir la physique du processus de génération des séismes. Parmi ces méthodes citées : celle d'équations intégrales (Boundary Integral Equation Method) en 3D est remarquable dans le sens où l'on est capable de modéliser la rupture dynamique spontanée dans un système de failles non-planaires plus réaliste que des séismes passés. La méthode de différences finies (Finite Difference Method) est la méthode la plus performante en terme du rapport qualité / coût : elle constitue un élément essentiel dans l'application sismologique et du calcul intensif à grand volume. Elle fournit un résultat raisonnablement fiable dans la plupart des cas (Bien sur, il y a encore des améliorations à apporter à cette méthode). Grâce à mes collaborations diverses, j'ai eu l'occasion de pratiquer d'autres méthodes telles que les éléments finis (Finite Element Method) ou les éléments spectraux (Spectral Element Method). Ces expériences très riches m'ont aidé à mieux comprendre non seulement le problème mécanique mais aussi le problème numérique.

La phase "dynamique" d'un tremblement de terre, soit "cosismique", se passe dans un très court moment par rapport à la période du cycle sismique d'un grand séisme inter-plaque ou intra-plaque (Figure 2.5). Il doit y avoir plusieurs phases différentes de la phase dynamique et chacune d'entre elles sont liées l'une à l'autre. Ma recherche se concentre principalement sur la période cosismique, où sont générées les ondes sismiques et pour résultat, un désastre conséquent. Cependant, il me paraît aussi important de savoir comment un grand séisme se prépare pendant le cycle sismique (soit "intersismique" et "présismique"), comment la Terre continue à se déformer après le séisme (c'est-à-dire en "postsismique"). L'approche géodésique est aussi important que l'approche sismologique, comme exposé dans la Figure 2.6. Mécaniquement, on peut décrire que la période intersismique correspond à la concentration de contrainte sur la faille, la phase presismique correspond à l'arrivé d'une instabilité, la phase cosismique correspond à la libération et à la redistribution de contrainte, et enfin la phase postsismique correspond à la relaxation de contrainte. C'est un sujet de mécanique de milieux continues (élastique, visco-élastique, etc.) avec l'interaction spatio-temporelle des failles.

En outre, les expériences dans les laboratoires ont démontré que pendant le cycle sismique, le comportement de faille, la loi constitutive de faille ou la loi de frottement peuvent varier largement

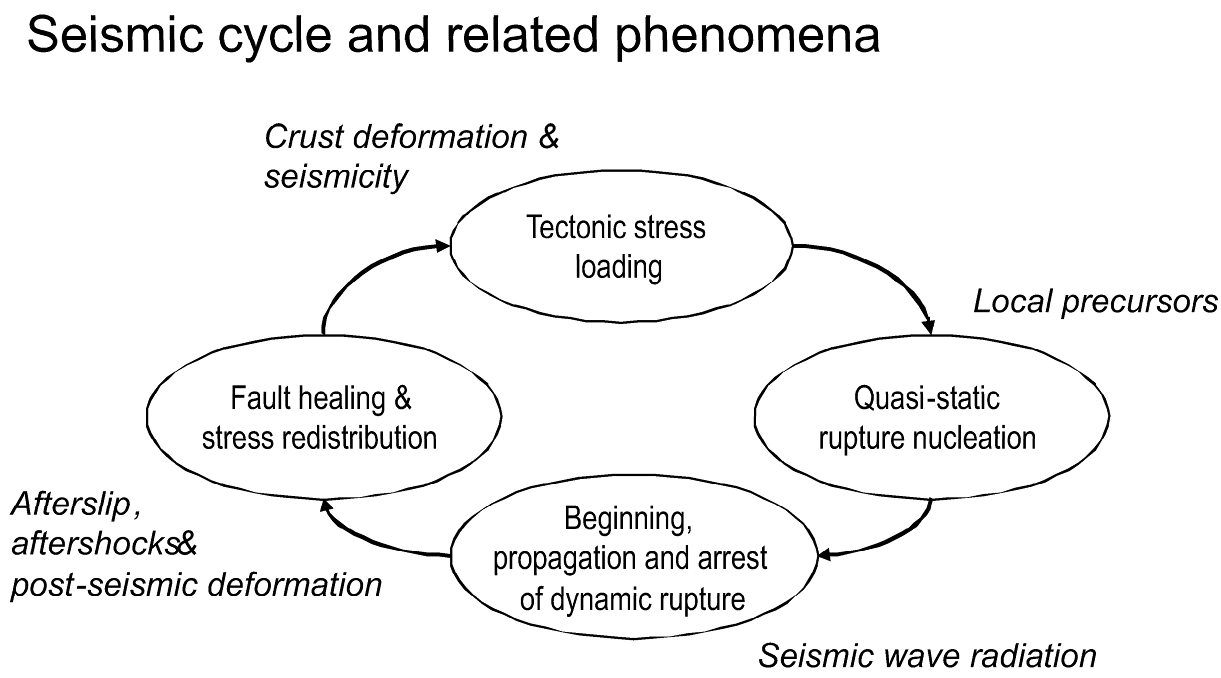


FIGURE 2.5 – Four main phases constituting a seismic cycle of repeated large earthquakes. Modified after Ohnaka and Matsu'ura (2002). My research field essentially belongs to "dynamic rupture" which appears visibly as "wave propagation" in front of us. Although this part is essential in seismology, we do not have to forget the other parts of a seismic cycle. They should have a causality from one to another.

en fonction de la contrainte chargée, du mouvement de faille (glissement, taux de glissement) et d'autres facteurs environnementaux tels que la température, l'existence de fluide etc. Une autre question se pose donc : Comment le comportement de faille se évolue-t-il et comment les paramétrer le long de la faille sont-ils ? La réponse à la question conditionnerait le processus du séisme. Le Chapitre 5 est ainsi dédié à la partie principale de ma recherche, la compréhension de la physique de génération d'un séisme sur des failles. L'étude théorique sur l'évolution du comportement de faille était le premier sujet de ma recherche, notamment l'étude sur comment la faille récupère sa résistance après une chute pendant le séisme.

Le concept de la loi constitutive dépendante du glissement et du temps se base sur le mécanisme de l'abrasion et l'adhésion de surface de faille à topographie complexe et explique l'affaiblissement pendant la rupture dynamique (slip-weakening) ainsi que la dépendance de la résistance sur le taux de glissement (velocity-weakening) et sur le temps de contact (log t healing). En supposant une telle loi sur la faille, j'ai appuyé mes études numériques sur la rupture dynamique des failles à géométrie complexe. Un bon exemple de l'étude complète est montré pour le séisme de Landers en Californie en 1992 où la rupture traversait les trois failles principales en parallèle. Par rapport à ces études dites "macroscopiques" pour les grands séismes, il ne faut pas oublier l'hétérogénéité

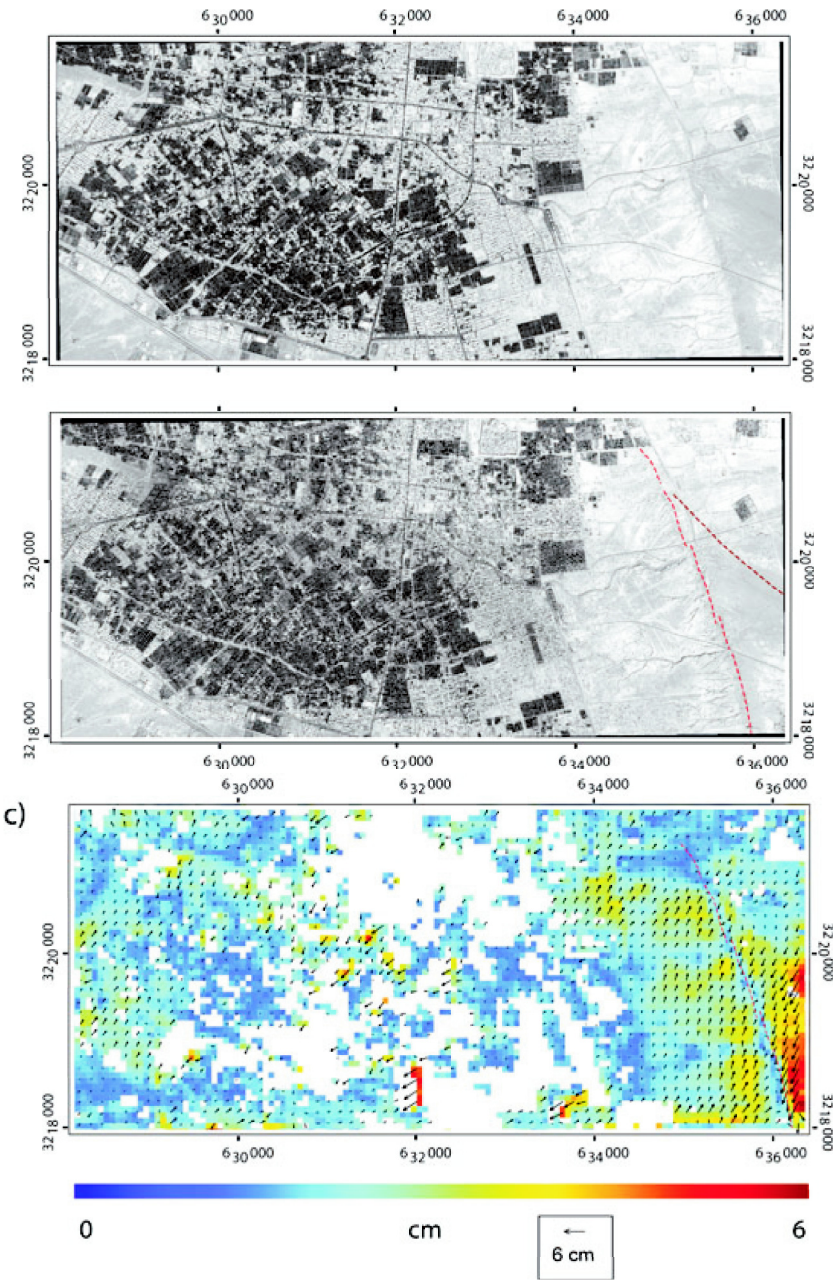


FIGURE 2.6 – Quick bird images around the city of Bam before (top) and after (middle) the 2003 M6.5 Bam earthquake and the coseismic correlogram in absolute displacement field with its direction. An oblique reverse fault is found along a broken red line. After De Michele et al. (2008).

sur la faille en petite échelle. La loi d'échelle à différentes tailles de séismes en sismologie devra être comprise par la loi d'échelle qui doit exister sur la faille. Le concept de la loi constitutive de faille est une idée fondamentale, qui est en fait décrite par la superposition de différentes longueurs d'ondes caractérisant le comportement de faille. C'est le sujet de ma recherche actuelle. J'aborde par exemple les questions suivantes : Quelles sont les différences entre les petits et les grands séismes ?

Comment la faille évolue-t-elle suite à la sismicité de tels séismes ?

Le développment de la méthodologie numérique en sismologie et la compréhension de la physique du processus de génération des séismes représente non seulement un grand challenge scientifique mais aussi une contribution importante et pratique pour l'étude de l'aléa et le risque sismique. Pour cet objectif, l'essentiel est de pouvoir prédire le mouvement fort le plus quantitativement possible.

Il est constitué de deux éléments : l'estimation de scénario de source sismique et la modélisation de la propagation des ondes à partir de cette source jusqu'au site d'intérêt. Pour le premier, la description "cinématique" de source sismique a été largement étudiée par différentes équipes et elle a eu de grands succès en application. Il reste cependant à évaluer la consistance avec la physique, car la description est déduite principalement à partir des analyses des séismes passés. Pour le deuxième, alors que le calcul de la propagation des ondes dans le milieu élastique est toujours le centre de la sismologie, l'approche n'est pas toujours basée sur les équations des ondes (déterministe). Les ingénieurs prennent souvent un autre moyen empirique ou stochastique pour deux raisons principales. Une est que l'approche déterministe est limitée à une bande serrée de fréquence à cause des informations insuffisantes de structure (où les ondes se propagent) et de ressource numérique. Une autre raison est que les ingénieurs cherchent surtout un moyen simple et standard applicable universellement. C'est rare qu'ils cherchent un mouvement extrême sous une situation spéciale telle que le champ proche de faille, qui dépasse la norme parasismique. Malgré tout cela, il serait impératif d'adopter l'approche déterministe, stochastique et/ou empirique selon le besoin, la connaissance et l'incertitude du contexte. Il est important d'apprendre comment l'approche déterministe est valide (ou limitée) lors de séismes passés ; comment choisir la méthode la plus adéquate sur un site d'intérêt.

Le Chapitre 6 résume les travaux récemment effectués. C'était pendant mes post docs en France que j'ai premièrement eu la conscience concrète de ma recherche. Un axe concerne l'estimation de scénario possible de séismes dans un système de failles en considérant la nature de la rupture dynamique spontanée différente de la description cinématique. Une grande différence est la magnitude de séisme. Elle est le résultat de simulation de la rupture dynamique dans un système de failles non-planaires alors qu'elle est une hypothèse dans la description cinématique. Un autre axe s'oriente vers la modélisation de la propagation des ondes sismique à la façon déterministe. Je suis intéressé à étudier comment le mouvement fort est affecté par la rupture dynamique en champ proche, comment ma méthodologie s'approche de la méthode classique existante, comment expliquer le cas réel du séisme passé et comment simuler les futurs séismes.

Enfin, le Chapitre 7 représente la perspective de la recherche. J'expliquerai d'abord le programme de recherche au BRGM dont je suis en charge depuis 2005, puis mes recherches individuelles dans les autres chapitres : recherche fondamentale sur le processus de la génération de séisme et recherche appliquée sur l'évaluation d'aléa sismique.

Chapitre 3

Originalité des recherches (Originality)

Beaucoup d'études sur la source sismique sont faites d'un point de vue cinématique. Hideo Aochi a réussi à construire une méthode d'équations intégrales évitant la singularité forte dans le milieu élastique homogène en 3D et cette nouvelle méthode est capable de traiter dynamiquement le mouvement de rupture sur failles à géométrie arbitraire, d'une manière flexible. Elle a ouvert une nouvelle voie dans la modélisation des failles non planaires.

La géométrie complexe de failles observées sur la surface de la Terre et la structure de failles segmentées représente un aspect important dans le processus de la rupture sismique. La recherche de Hideo Aochi a permis de créer un lien entre l'aspect quantitatif et les données observées, ceci sans doute amène les études de la source sismique dans une nouvelle dimension.

Le fait marquant est l'applicabilité de sa méthode en risque sismique, la prédiction du mouvement fort en champ proche en haute fréquence, qui est très sensible à la géométrie de faille. Hideo Aochi a également commencé à travailler sur le modèle de source sismique plus pratique au travers des collaborations avec les ingénieurs en génie civil.

Les grands séismes intra plaques ont lieu en interaction entre plusieurs segments de faille. Il est devenu possible de simuler quantitativement le transfert de rupture dans un tel système de faille. Hideo Aochi a obtenu dans ce domaine des résultats probants : sa modélisation des failles non-planaires a permis de comprendre lors d'un séisme, l'effet de la contrainte normale et du changement de géométrie de faille sur la propagation spontanée de rupture dans des failles branchées.

On découvre surtout l'originalité de sa recherche dans la comparaison entre les sismogrammes synthétiques calculés par son modèle et ceux observés. Prenons par exemple le séisme de Landers en 1992, Hideo Aochi a obtenu grâce à sa méthode de comparaison, la force cohésive dans le frottement et la distribution hétérogène de la contrainte initiale. Le comité souhaite que Hideo Aochi continue sa collaboration avec les sismologues japonais afin de progresser davantage dans ce domaine.

(Le commentaire ci-dessus est traduit du comité "Seismological Society of Japan" pour le prix jeune sismologue en 2007, d'après Newletter SSJ, vol.19, no.1, le 10 mai 2007, texte original en japonais)

Chapitre 4

Numerical Methods

4.1 Introduction

The solution of the system of elastic (occassionally inelastic) equations for all aspects of earthquakes is a classical problem. For the earthquake source, the problem remains difficult mainly because the phenomena are very discontinuous and the boundary conditions should be non-linear (See Chapter 5). These problems require highly accurate estimates of the stress and fault movement on the fault plane itself. On the other hand, for seismic wave propagation in an elastic medium, theoretical and numerical studies are relatively well established as seen in many textbooks (e.g. Aki and Richards, 2002). It is important to model realistic heterogeneous media and, in addition, the numerical method should be scalable for large computers. To study site effects, complex geometrical and material configurations require a stable and sophisticated numerical method.

I have been working on different methods, which will be reviewed in the following sections : boundary integral equations, finite difference, finite element, spectral element and hybrid methods. The selection of one of the above methods depends on our purpose. Through my experiences I must say that all numerical methods are no more than approximations and their correct use requires experience and a physical understanding of the method. The coherence between solutions from different techniques is often emphasized in benchmarking project. However, I think that what is more important is the sensitivity of each method to given input parameters and consequently inherent differences in the solutions, which are rarely shown in publications. It is always important to make an effort to achieve to a better solution while it is also necessary to measure and understand the differences between solutions. In the framework of the French national project SEISMULATORS (2006–2008), simple comparison exercises have been carried out on different methods for 2D dynamic rupture problems. The solutions of all the methods converge when the model parameters are properly tuned (and when we know what we want to obtain). However, it is important to notice that their discretizations are in principle different. Therefore, it is quite normal that there

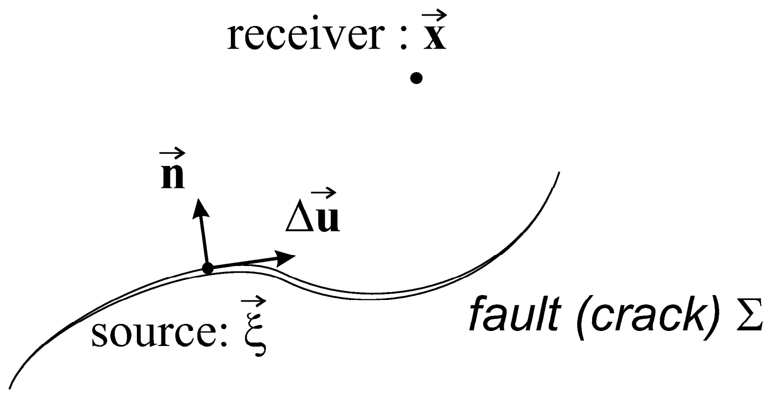


FIGURE 4.1 – The basic concept of BIEM. In a linear elastic medium (ignoring the far-field outer boundary), the displacement field at any point $\vec{x}$ can be written by a spatio-temporal convolution of the fault slip $\Delta\vec{u}(\vec{\xi})$ along the fault surface Σ ($\vec{n}$: normal vector) and the response function (Green's function). This is the representation theorem (e.g. Aki and Richards, 1980).

remains some discrepancy between solutions (Aochi et al., 2009). I think that understanding these differences is essential in addition to the effort to obtain similar solutions. So which method is the best ?

4.2 Boundary Integral Equation Method

Traditionally, the Boundary Integral Equation Method (BIEM), whose basic idea is shown in Figure 4.1, is a superior scheme for some problems with the following characteristics : linear governing equations, wave propagation, unbounded media, cracks or moving or unknown boundaries (Bonnet, 1995). The dynamics of a complex fault system has some of these characteristics. The BIEM that I have worked on since my PhD thesis has the same characteristics as Cochard and Madariaga (1994), Fukuyama and Madariaga (1995, 1998), Tada and Yamashita (1996, 1997), Kame and Yamashita (1997, 1999) : formulation in the time domain ; an expression for the stress tensor ; Green's function in homogeneous, infinite elastic medium ; and discretization with constant slip velocity on a spatial and temporal unit. One of the practical reasons I began using this method is my close relationship with some pioneers of the approach (namely Professor Teruo Yamashita and Drs Taku Tada, Nobuki Kame and Eiichi Fukuyama) during my PhD thesis. However, I am convinced that this technique is still the most useful for faulting problems. The technical detail of the approach is given in Aochi (2000) and Aochi et al. (2000a).

Its principal advantage is that it is able to treat rupture propagation along non-planar faults in a 3D medium, as shown in the first application for the 1992 Landers earthquake (Aochi, 2000 ; Aochi and Fukuyama, 2002) and in various subsequent applications ; these are discussed in Chapter 5. Figure 4.2 shows snapshots of the dynamic rupture simulation of the 2007 Chuetsu-Oki, Ja-

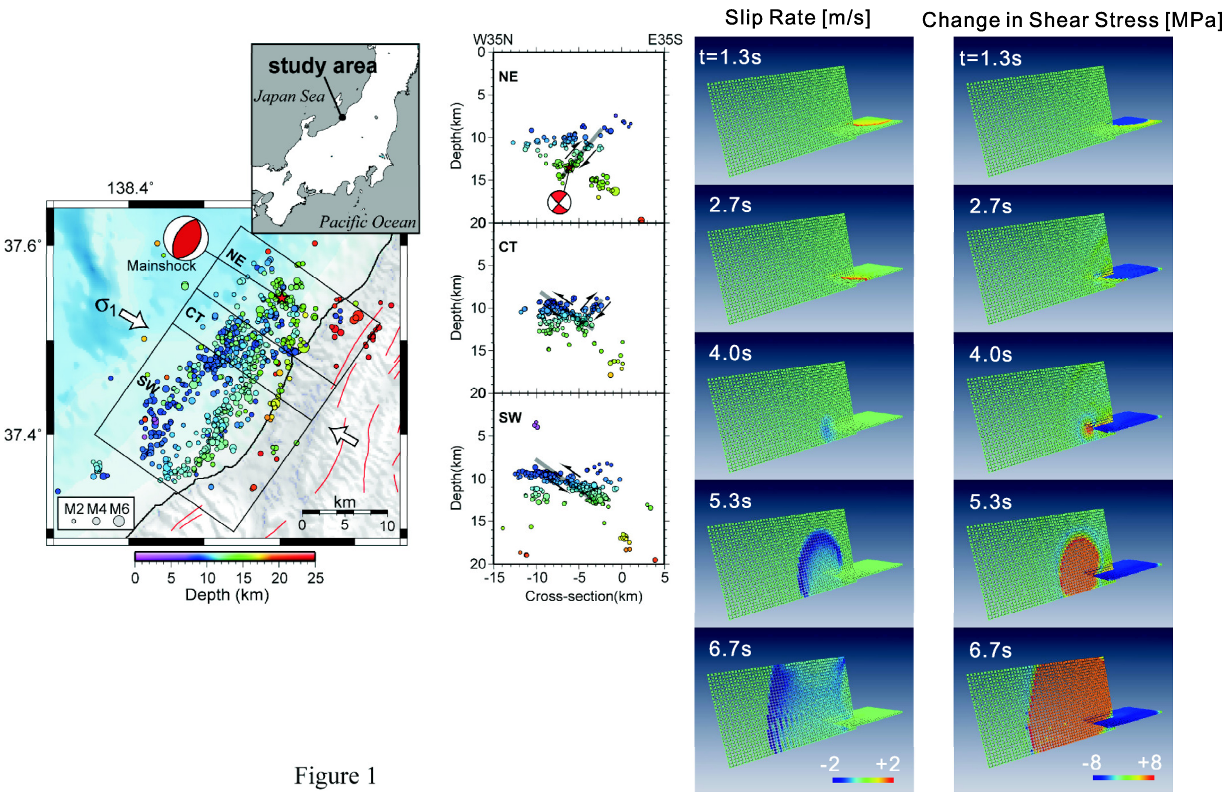


FIGURE 4.2 – Example of a BIEM simulation for the 2007 $M_w6.7$ Chuetsu-Oki, Japan, earthquake. The fault system is inferred to be segmented as shown in the left panel and this can be simulated by the BIEM in the right panel (Aochi and Kato, 2008). The rupture begins at the small northern segment dipping to the north-west and transfers to the large southern segment dipping to the south-east. Two segments are cross-cutting conjugate fault planes.

pan, earthquake, showing dynamic rupture transfer between cross-cutting conjugate fault segments (Aochi and Kato, 2008). A similar technique has also been applied to the 1999 Izmit earthquake (Aochi and Madariaga, 2003) and to possible earthquake scenarios on the complex Middle Durance, France, fault system (Aochi et al., 2006). As seen in this example, because of the analytical formulation, the method is efficient for complex fault geometries such as joint, branching or segmented, as well as, curving systems. It should also be noted that Cruz-Atienza et al. (2007) firstly succeeded in comparing their finite difference method with the BIEM in 3D rupture problems. The weak points of the method (Aochi, 2000) is its square-shaped discrete element and defining the Green's function in an infinite medium. However, these points have also been improved by different groups. Fukuyama et al. (2003) are able to model using triangular elements, which allows the simulation of large subduction earthquakes with realistic 3D geometry. Zhang and Chen (2006a, b) introduce the Green's function for a semi-infinite medium to successfully simulate a thrust fault rupturing the ground surface. We have also tried to develop a hybrid type simulation method to

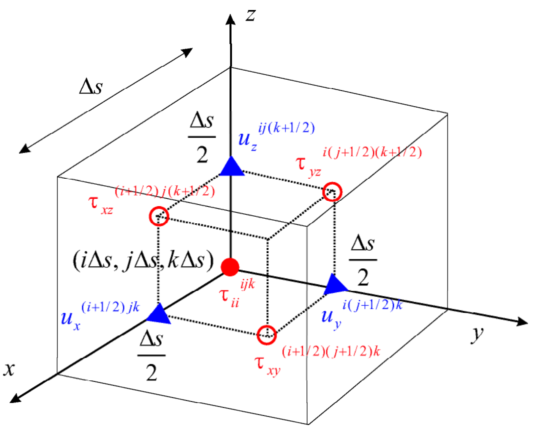


FIGURE 4.3 – Schemtaic illustration to explain the standard staggered grid in FDM. Diagonal components of stress τ_{xx}, τ_{yy} and τ_{zz} are given on a grid with material properties such as density. Shear components of stress τ_{xy}, τ_{xz}, τ_{xy} and velocities (derivatives of displacement) v_x, v_y and v_z are shifted by half a grid spacing.

study semi-infinite and/or heterogeneous situations (Kame and Aochi, 2008 ; See section 4.5).

4.3 Finite Difference Method

The Finite Difference Method (FDM) is the most convenient scheme to efficiently model seismic-wave propagation. It should not be a surprise that I began studying this topic when I was in the laboratory of Professor Raul Madariaga. We first used the approach in Aochi and Madariaga (2003) for a simulation of the 1999 Izmit earthquake. Our aim was to simulate the radiated seismic waves rather than the dynamic source process ; although FDM has also often been applied for dynamic rupture simulations (e.g. Virieux and Madariaga, 1982 ; and many others). The code used is written based on a staggered grid (Figure 4.3) of 2nd and 4th order in space (Virieux and Madariaga, 1982 ; Levander, 1988) and the Perfectly Matching Layer (PML) absorbing condition (Collino and Tsogka, 2001). Other technical details are discussed by Graves (1996). In fact, it is very easy to include any kinematic source (point or finite source) in the FDM simulation so that several studies of the ground motion in the near field of earthquakes have been made using this technique and we have also used it within seismic hazard assessments. For example, Le Puth (2005) uses this technique to study a local earthquake (a $M4.5$ event in 2001) near Nice, south-eastern France, using 3D geological and topography model ; this study is now being reconducted using a newly-constructed 3D geological model (projects QSHA and NUMASIS). Another local earthquake studied was a 2005 $M4.5$ event in the metropolitan area of Tokyo. For a station located at a depth of 3000 m in the Koto area, it is surprising to see that the observed seismograms can be very easily reproduced

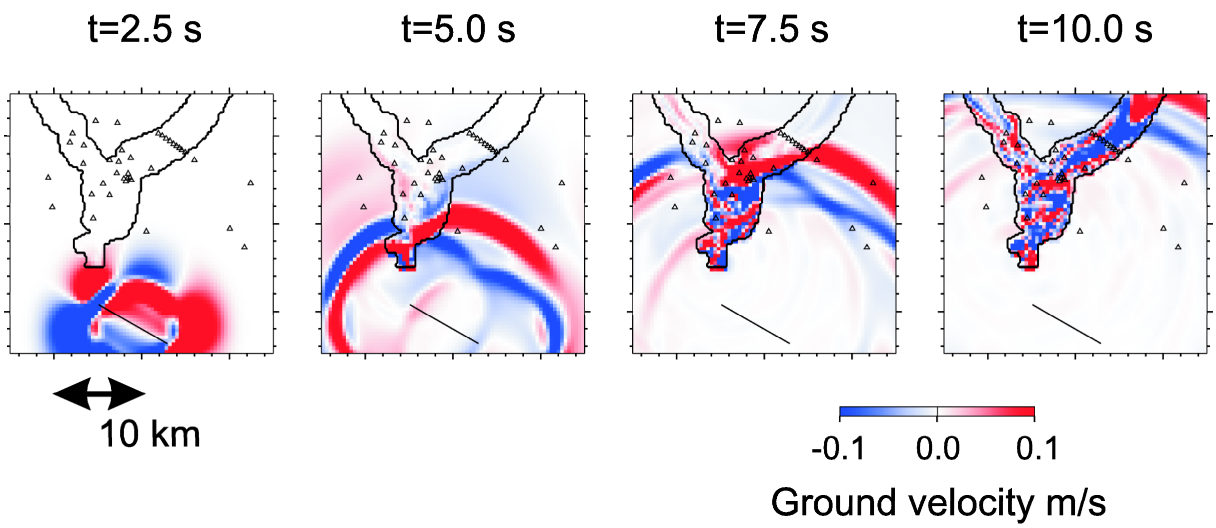


FIGURE 4.4 – Snapshots of a FDM simulation for wave propagation (ground velocity in the x-direction) from a kinematic earthquake source in the Grenoble area. The source location (a strike-slip fault) is mapped as a black line and the triangles show the receiver positions studied. The Grenoble basin outline shows a "Y" shape in the middle of the model, where the wave velocity is about 10 times slower than in the surrounding bedrock. Thus, the ground motion in the basin is significantly amplified and the duration is much longer (Aochi et al., 2006).

(Aochi and Ide, unpublished manuscript, 2005). Figure 4.4 is an example of wave propagation simulations for a scenario earthquake near the Grenoble basin (Aochi et al., 2006). The basin effect is clearly observed in the amplification and the duration of the ground motion. Jousset and Aochi (2006) and Salichon et al. (2008) have worked on simulating the shaking from the 2004 Les Saintes, Lesser Antilles, earthquake ($M6.3$) considering the topography, bathymetry and the sea. However, the simulations do not closely match the observations due to the lack of a good structural model. Other applications are found in Aochi and Douglas (2006), Douglas et al. (2007) and Imperatori et al. (2008) for the study of near-field strong ground motions compared with empirical ground-motion prediction equations (See Chapter 6).

This method is always being improved within the framework of BRGM R&D projects (Ducellier and Aochi, 2007a, 2007b ; Dupros et al., 2008), including : the optimization for parallel computing ; the implementation of visco-elastic media for realistic attenuation ; and the improvement of the free-surface condition. The absorbing boundary condition has also be improved using the Convolution Perfectly Matching Layer (CPML) following Komatitsh and Martin (2007).

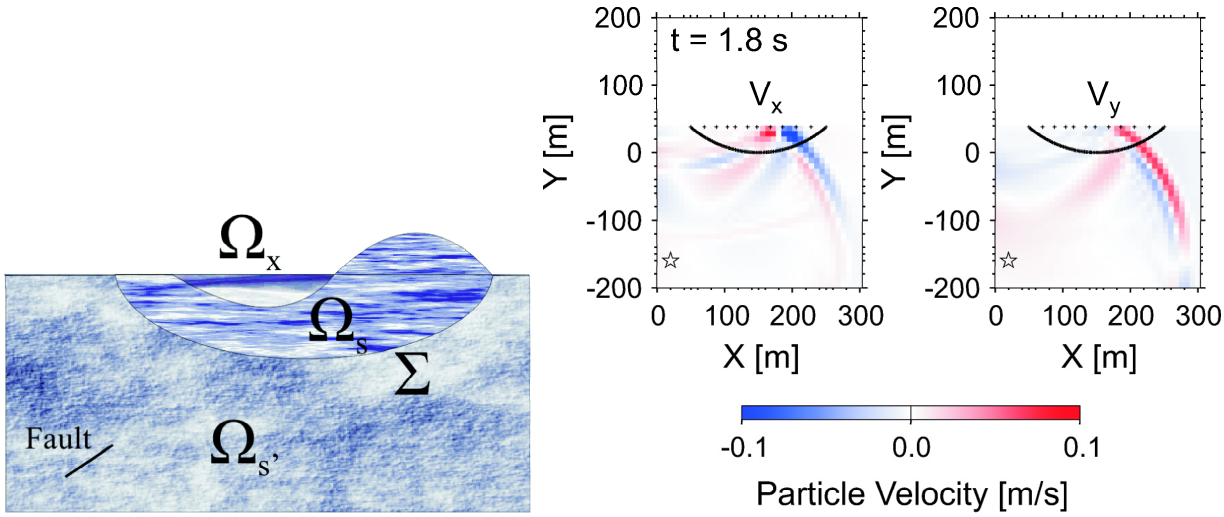


FIGURE 4.5 – [Left] Schematic illustration showing the coupling between an FDM and an FEM. Domain $\Omega_{s'}$ including the seismic source are calculated by an FDM. Domain Ω_x (non-linear soil) and Ω_s (elastic medium) are calculated by an FEM through the boundary condition on Σ given by the FDM. This is a sequential simulation under the assumption that disturbances generated in Domain Ω_x and Ω_s do not affect the global field of wave propagation in $\Omega_{s'}$. [Right] Snapshot of a wave propagation simulation (FDM) from a point source (star). The free surface is situated at $y = 20\,\text{m}$. Wave-field along an arc is input into a local ground-motion simulation (FEM) shown in Figure 4.6. Figure after De Martin et al. (2007).

4.4 Finite Element Method and Spectral Element Method

The Finite Element Method (FEM) and its special derivative, the Spectral Element Method (SEM), are a type of alternative scheme. My first attempt to use the FEM (code CHIKAKU, `http ://www.riken.go.jp/lab-www/CHIKAKU/`) was in about 2000 in Japan in order to adopt it to model earthquake faulting. However, this code was originally developed to consider plastic deformation with industrial pressing. We found that it was not suitable for the problem of the interface in a continuous medium, such as an earthquake fault.

The second occasion when I used it was not for the earthquake source but for the modelling of site effect ; thanks to Dr Fabian Bonilla of IRSN. The code FLIP (Iai et al., 1992a, b) (`http ://cdit.org.jp/products/flip.html`) can model soil liquefaction during earthquake shaking. This code requires some preparation in advance of analyzing 2D dynamic soil behavior : besides the initial condition, we need a boundary condition that should be used for a 1D column with the same input ground motion (no absorbing condition and no cyclic condition). We tried modeling the lateral spreading observed during the 1999 Izmit earthquake but, due to these complexities of use, the final results were computed using a FDM (Aochi et al., 2004).

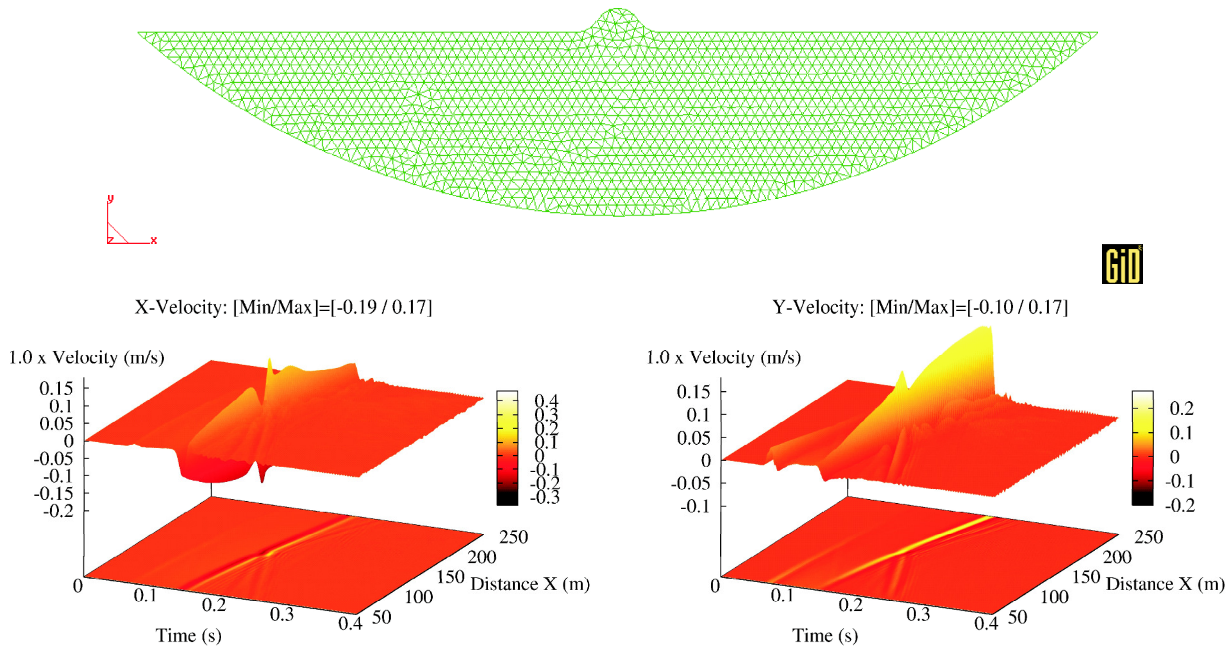


FIGURE 4.6 – Coupled simulation of FDM and FEMs to study the ground motion due to local topographic irregularity. The FEM domain (top panel) corresponds to the inside of an arc shown in Figure 4.5. Synthetic ground velocity wave forms are shown below along the free surface of the model.

Therefore, it is at BRGM where I really began working with FEMs, after encountering Dr Hormoz Modaressi and his colleagues, who have worked for a long time on various geomechanical problems using FEMs (e.g. using the code Gefdyn : `http ://www.mssmat.ecp.fr/`). This code was developed for the purpose of non-linear soil dynamics and it is therefore suitable for studying site effects under seismic ground excitation. It is a well-known application where one gives a single input ground motion at the bottom of the model assuming a vertically-incident plane wave. This corresponds to the situation where an earthquake source is far enough from the site of interest. Site effect studies are at the center of seismic risk assessments, as we will see in a later chapter. Speaking numerically, I would like to emphasize here the development of hybrid techniques for studying, not only site effects, but also source and propagation effects for seismic signals (see the next section).

On the other hand, we have tried applying this classical FEM code Gefdyn for the dynamic rupture process of the earthquake source (Bernardie et al., 2006 ; Arezou Modaressi, personal communication, 2007 ; Aochi et al., 2009). The code Gefdyn includes an interface element, so called 'joint element', which is often used in soil dynamics. Inelastic deformation, corresponding to shear discontinuity along an interface, is allowed in this 'joint element' which is assumed to have no volume. This joint element has rigidity, independently of that of the surrounding medium but this parameter is difficult to control correctly. Another technique for modeling faulting with FEM and SEMs is using splitting nodes at both sides of the fault plane. For the necessity of comparison, the code SPEC2D based on the spectral element method (SEM) written by Dr Gaetano Festa is used (Manglou, 2007). Although there are clear differences in fault treatment, gridding, and the interpolation function, the main aim of the two methods should be to seek the proper solution within their frameworks. The FEM looks for a solution suitable for the global field while the SEM solves the equation locally as in the FDM and BIEMs. This is also discussed in Aochi et al. (2009).

4.5 Hybrid Methods

As each method has its advantages and disadvantages, I prefer the idea of a kind of hybrid approach. This was first proposed by Olsen et al. (1999) : the dynamic earthquake source simulated by the BIEM and introduced into a FDM scheme to model dynamic rupture and radiated wave propagation. This hybrid BIEM-FDM simulation scheme is very successful for modeling earthquakes as will be shown in Chapters 5 and 6 (Madariaga, 2003 ; Aochi and Olsen, 2003 ; Aochi and Douglas, 2006).

A hybrid BIEM-FDM concept is also adopted to simulate dynamic rupture processes in a heterogeneous medium, which cannot be modeled by the original BIEM founded in a homogeneous, infinite medium. The idea is simple. There are no analytical kernels (Green's functions) for waves travelling in a heterogeneous medium. Thus the FDM calculates them for part of the integral equations. A similar approach is tested in Goto and Bielak (2007) using an FEM in the framework of the BIEM. However, their approach is not validated in a homogeneous medium. Kame et al. (2007) calculate the numerical kernels accurately enough by comparing them to the analytical solution in an infinite, homogeneous medium. It is found that FD grid spacing needs to be about a hundred times smaller than the target BIEM element size. Then the method is applied in a semi-infinite medium for thrust faulting approaching the ground surface (Figure 4.7 ; Kame and Aochi, 2008). Rupture acceleration is precisely simulated when it approaches the ground surface. This method may not be the best solution, but this corrects a drawback of the original BIEM and it is applicable for some interesting realistic configurations.

The next example is for local wave propagation and local site effect study. It may be insufficient to assume a plane wave incidence for studying site effects when taking into account near-source effects or complex medium effects in wave propagation. For such situations, one must prescribe a more realistical variation in the input ground motion along the boundary within which the local ground shaking in the 2D or 3D domain is simulated by an FEM, for example. Here, as shown in Figures 4.5 and 4.6, we are able to couple FDM and FEMs for seismic wave propagation (De Martin et al., 2007). This is adequate to study effect of the incidence wave for local site studies. We note that

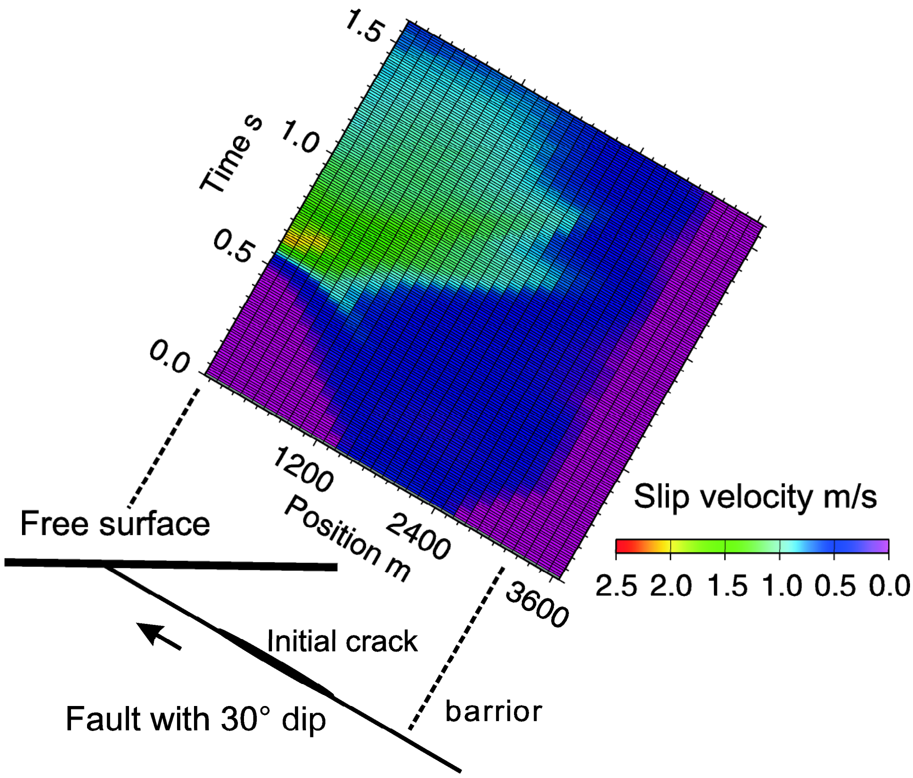


FIGURE 4.7 – Examples of 2D HDBM simulations of a dipping fault approaching the free surface (modified from Kame and Aochi, 2008). The rupture accelerates in terms of rupture velocity and slip velocity when approaching the ground surface due to the reflected wave from the surface.

this example is a sequential simulation procedure one after another through boundary condition between the two domains. Furthermore, Ducellier and Aochi (2009) demonstrate a truly hybrid simulation where the FD grids and the FE elements are interconnected, following the technique of Ma et al. (2003). These attempts are useful, because FDM costs much less than FEM for wave propagation at a regional scale and because FEM has an advantage of accurately modeling ground shaking for complex local situations, such on topographic relief.

Chapitre 5

Physics of the Earthquake Generation Process

5.1 Introduction

I remind the reader that all the numerical methods on which I have been discussing in the previous chapter are to better understand the complex mechanisms of earthquake phenomena. I am particularly interested in the earthquake source, which is brutal dynamic rupture process in the elastic Earth, releasing a part of tectonic stress accumulated due to the Earth's evolution. This is the origin of seismic wave radiation, as well as crustal deformation. As cited previously, the traditional seismological description (the representation theorem) represents complex fault rheology in the form of a fault constitutive law attributed along the fault plane (normally with no volume), namely inelastic behavior is defined as the earthquake source. This is also what linear fracture mechanics tells us. Based on this description, Figure 5.1 shows how to approach such an earthquake source through the numerical methods presented in the previous chapter. However, the behavior becomes complex principally due to the non-linearity in the fault constitutive law, the interaction of fault segments and other effects. In the following sections, it is worth of beginning with the questions : how to represent these conditions and how to solve the system interaction. The topics shown in this chapter have been studied since my master thesis. Most of my understanding is thanks to my earlier period with Professor Mitsuhiro Matsu'ura and the weekly seminar on "Earthquake Generation Process" with collaborators at the University of Tokyo. Therefore, the following is consistent with the recent textbook by Ohnaka and Matsu'ura (2002).

The objective of this chapter is to understand the earthquakes generation process, so the following question is always posed : how well can we reproduce earthquakes based on a physical description and the known geological situation ? I begin the Chapter with reviewing different aspects of earthquake dynamics and this fundamental question, related with the predictability of

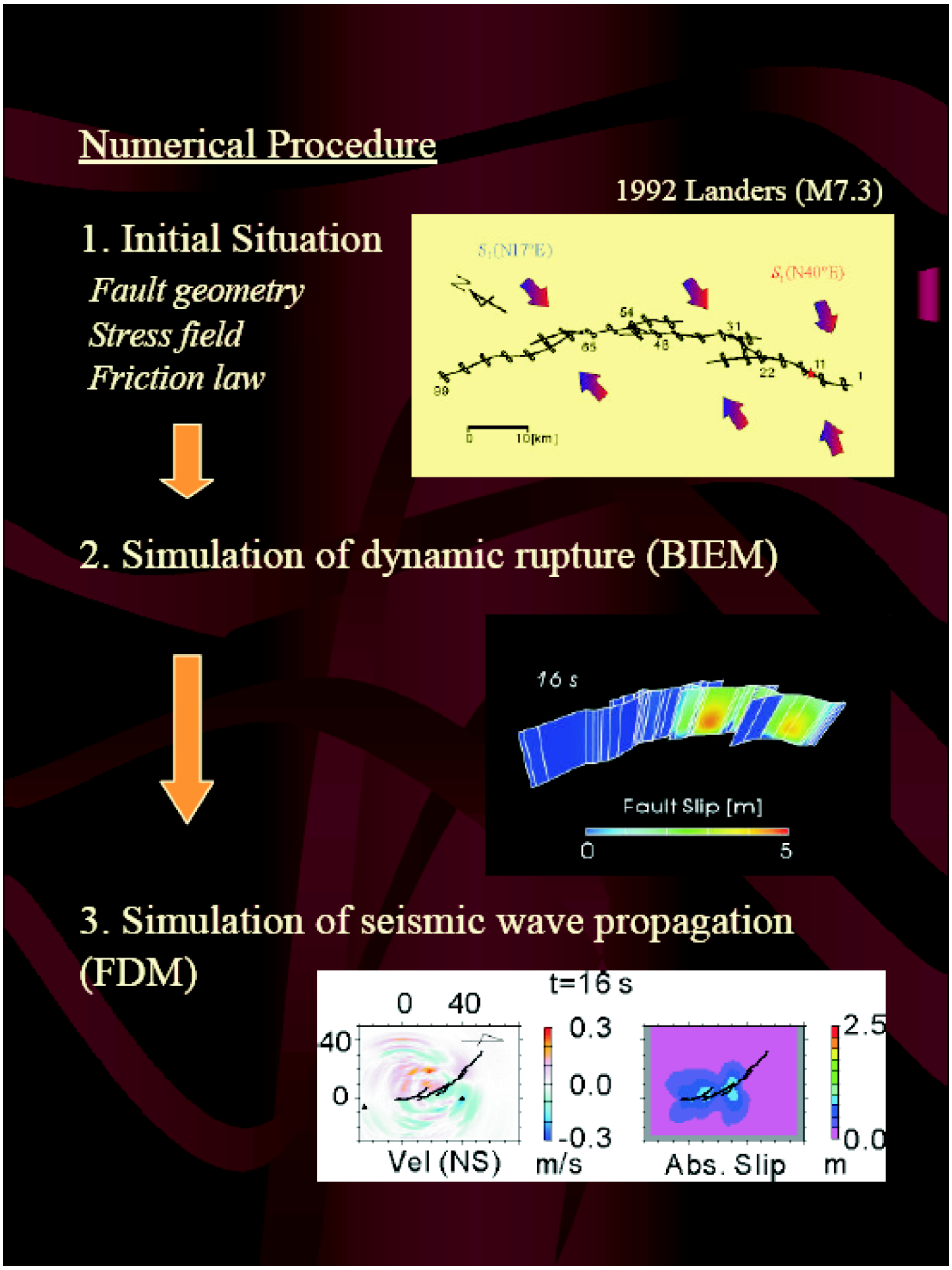


FIGURE 5.1 – Schemtaic outline of dynamic simulations of earthquakes. We need the fault geometry, the stress field and a fault constitutive law as the initial and boundary conditions. Then we are able to model dynamic rupture propagation on a complex fault system using, for example, the BIEM. Finally this allows us to discuss the seismic wave radiation from the faults using the FDM. The figures presented here are for the simulation of the 1992 Landers earthquake (Aochi and Fukuyama, 2002 ; and others. See the last section of this chapter). Figure after a presentation in 2002.

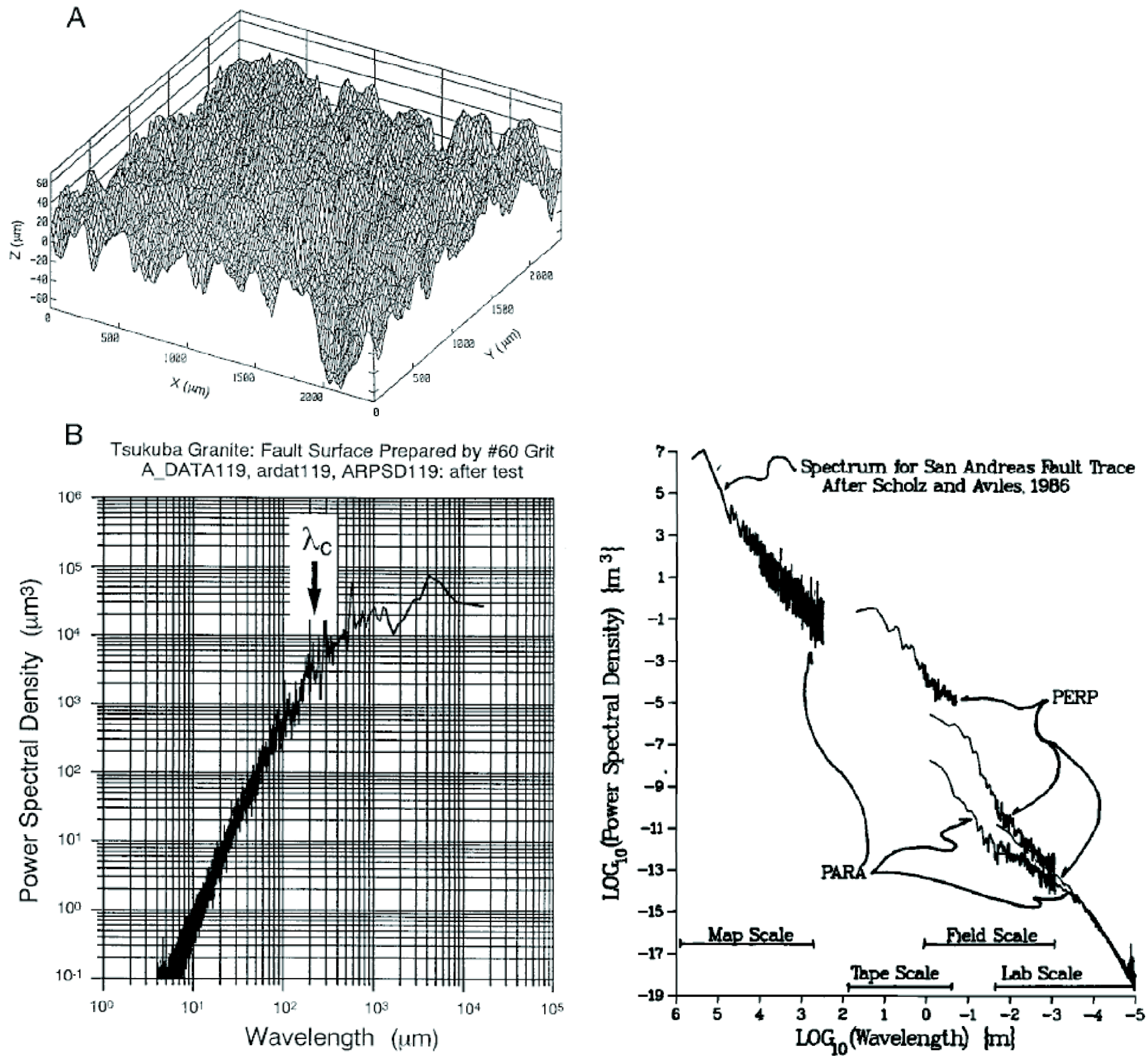


FIGURE 5.2 – [Left] (A) Rock surface profile and (B) power spectral density calculated for the fault surface against wavelength. λ_c indicates the corner wavelength, which is found to be proportional to D_c. After Ohnaka (1996). [Right] Power spectra for the fault surface over 11 orders of magnitude in wavelength. PARA-spectra for profiles parallel to slip direction, PERP-spectra for profiles perpendicular to slip direction. After Power et al. (1987).

earthquakes, will be discussed in the last section. First of all, it will be helpful to mention that the basic interest of a series of my studies is with “geometry”. It is widely known that any surface (rock or fault) is not a “plane”, but has some roughness at any scale, as shown in Figure 5.2. When this roughness is recognized macroscopically as fault traces and structure, they should be treated directly in the mechanics. This corresponds to my numerical works on non-planar fault systems. On the other hand, fault roughness cannot be treated deterministically at shorter scales. This microscopic feature should be included in the forms of the fault constitutive law. This starts with the mechanical concept of a slip-weakening law and then leads to the multi-scale fault heterogeneity problem.

5.2 Fault Constitutive Law

The first question is : what is the fault constitutive law ? It is known that an earthquake releases part of the accumulated stress, so that stress (fault strength) decreases during an earthquake rupture over several seconds. Then, stress accumulates again during a long time, as an earthquake rupture repeats on the same fault from the point of view of tectonics. This means, fault strength repeats "weakening" and "strengthening" processes as stress is released and accumulated. There are huge variations in time and in space during this cycle. One can never reproduce such a wide range of variations in laboratory experiments. This scaling issue is one of the main topics that I have investigated in my research. Regardless of the scale difference (for example, fault length in cm (laboratory) to km (field)), it should be noted that the slip rate is usually around 1m/s and the velocity of rupture propagation is a few km/s. This implies the existence of some scaling relation in the dynamic rupture process.

Another question arises : whether earthquake rupture is friction between two materials or fracture in an intact solid, namely whether earthquake occurs on pre-existing weak planes or creates new fracture planes ? The former seems to be true from the macroscopic view of tectonics, while the later is also true from the microscopic view of geology indicated by fault observations. Seismological analyses estimate that the fracture energy of earthquake takes a value between those of friction and intact fractures. This indicates that there occurs fracture in local rock, but due to the strong heterogeneity of the fault, the average fault strength becomes closer to frictional behavior. The fault constitutive law is, therefore, required to uniformly explain both aspects of intact fracture and friction.

Many rock experiments and seismological analyses support the "cohesive zone" hypothesis in shear rupture proposed by Ida (1972) and Palmer and Rice (1973). This is called the "slip-weakening law" in terms of the fault constitutive law, telling us that fault strength σ reduces with on-going shear rupture (slip discontinuity Δu) as shown in Figure 5.3. The reduction of the strength σ from the yielding stress (peak strength τ_p) to the residual stress τ_r is characterized by a finite slip D_c often called the critical slip displacement (or distance). In many numerical simulations, including most of mine, the following simplified formulate is assumed :

$$\sigma(\Delta u) = \tau_r + \Delta\tau_b(1 - \frac{\Delta u}{D_c})H(1 - \frac{\Delta u}{D_c}) \tag{5.1}$$

where $\Delta\tau_b$ is the breakdown strength drop, defined by $(\tau_p - \tau_r)$, and $H(\cdot)$ is the Heaviside function. This law seems simple enough but allows us to discuss physical quantities. The size of D_c is often

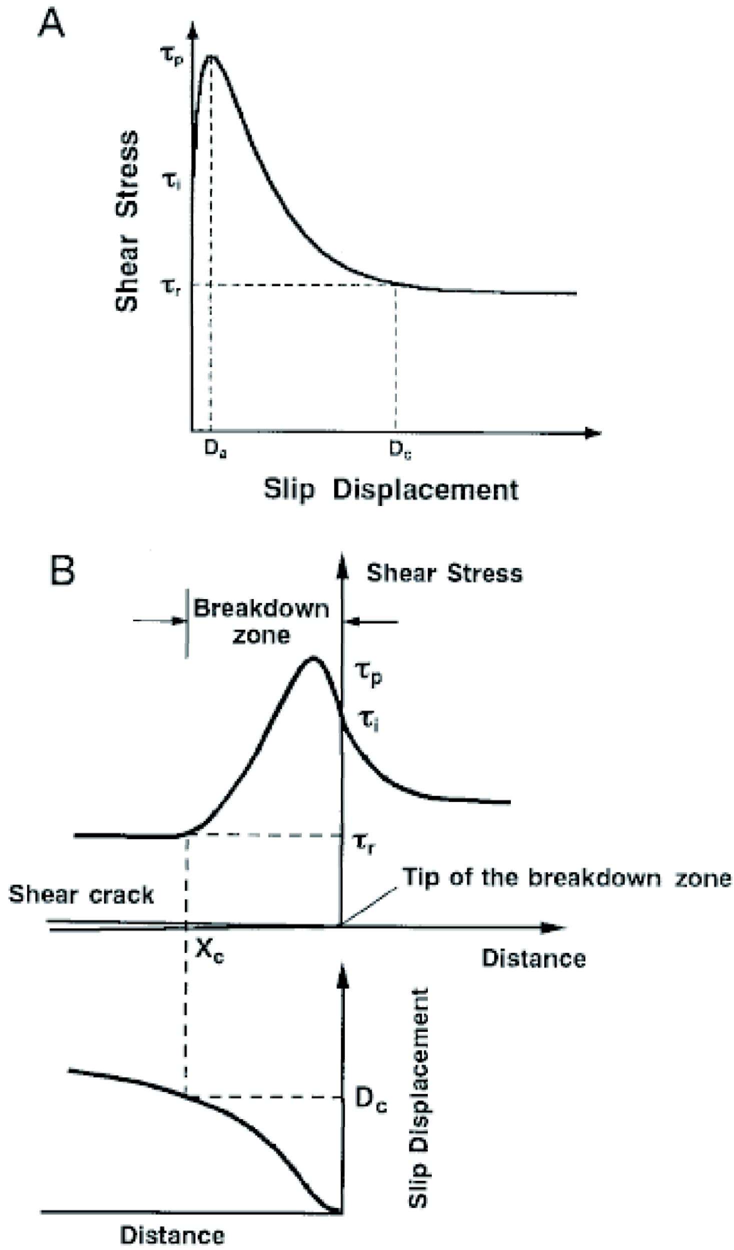


FIGURE 5.3 – (A) Constitutive relation, so-called "slip-weakening", for shear rupture. (B) Physical model for the breakdown zone near the shear rupture front, derived from the constitutive relation of A. There can exist a strengthening process before the weakening process ; however, the length scale is much smaller in the former ($D_a \ll D_c$). Therefore only the latter weakening process is usually discussed. τ_p is peak strength, τ_r is residual strength, D_c is critical slip displacement, X_c is the breakdown zone size. Figure after Ohnaka (1996).

estimated from near-field ground motion following Ohnaka and Yamashita (1989). By the way, the slip-rate dependency is not clear during dynamic rupture, as seen in rock experiments (e.g. Ohnaka

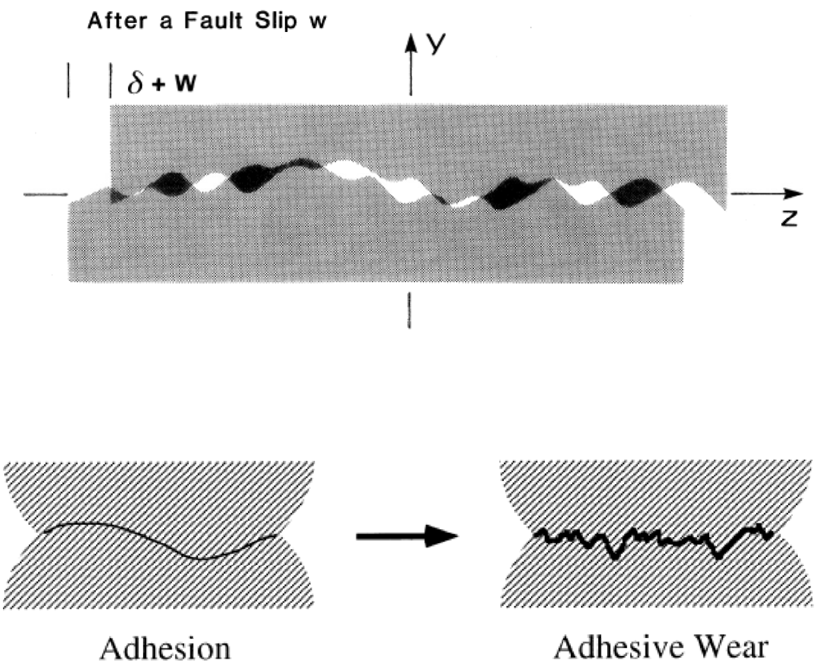


FIGURE 5.4 – Schemtaic illustration of the mechanism of abrasion and adhesion, leading to "weakening" and "strengthning (healing)" of fault strength. The "weakening" mechanism (top) has been proposed by Matsu'ura et al. (1992) and "healing" (below) is proposed firstly in Aochi (1997). (Figure after Aochi and Matsu'ura, 2002).

et al., 1986) and in seismological inversion analyses (e.g. Ide and Takeo, 1997). There are some slip-rate dependent fault constitutive laws essentially based on frictional experiments at constant low velocity. Such laws can also reproduce the "weakening" process of dynamic rupture. However, as reported by Bizarri et al. (2001), the parameters of the slip-rate dependent law become implicit in the slip-weakening behavior during dynamic rupture.

The question is how to physically explain this complex constitutive law. Matsu'ura et al. (1992) give an idea by focusing on the surface roughness, which is actually found to valid in precise rock experiments (Ohnaka, 1996 ; Ohnaka and Shen, 1999). It is found that the characteristic length λ_c of rock surface roughness controls the parameter D_c. The model of Matsu'ura et al. (1992) considers surface asperities of different wave-lengths and assumes that such asperities suffer abrasion with slip. My first theme during my master thesis was how the fault strength recovers after an earthquake. Aochi (1997) and Aochi and Matsu'ura (2002) introduce an adhesion process of contact surface (Figure 5.4). This concept is written in the mathematical form :

$$dY_k = -\alpha k Y_k dw + \beta k^2 (\bar{Y}_k - Y_k) dt \quad (5.2)$$

where Y_k is the spectral amplitude of the fault topography at wavenumber k and w and t represent

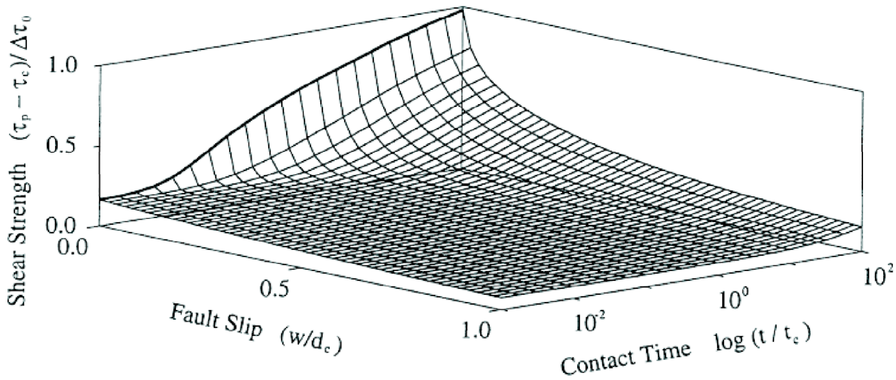


FIGURE 5.5 – Change in fault strength with fault slip during high-speed slip for different contact durations before the event. Fault strength heals as a function of $\log_{10}(t)$ and the characteristic slip displacement D_c is also restrengthed as a function of time. From Aochi (1997) and Aochi and Matsu'ura (2002).

fault slip and time, respectively. α and β are parameters representing abrasion and adhesion ratio, respectively. $\bar{Y}_k$ represents the maximum amplitude, a set of $\bar{Y}_k$ giving a power-low distribution. The fault strength is estimated by an integral over this function Y_k taking into account the asperity deformation (Matsu'ura et al., 1992). Equation (5.2) means that the fault roughness at smaller scales is easily lost by abrasion (Matsu'ura et al., 1992) and also recovered rapidly by adhesion (Aochi and Matsu'ura, 2002). In this recovery process, the smoothed fault surface is adhered strongly, so that the recovery of fault roughness means that different surface traces are created. The fault trace is identical in every recurrence of an earthquake in a macroscopic view, while local rupture paths may be different during each event in a microscopic view. This perspective should be important when considering the evolution of the fault (zone). Equation (5.2) is able to explain both the logarithmic strength healing (Dieterich, 1972) and the recovery of D_c with contact time (Figure 5.5). The velocity weakening of strength (Dieterich, 1978) can be also be shown by letting dw/dt = constant in Equation (5.2). The behavior of Equation (5.2) is studied in a spring-block system with a single degree of freedom and in a 2D in-plane dynamic rupture problem (Aochi, 1997 ; Aochi and Matsu'ura, 2002). The effect of β (adhesion) is limited once dynamic rupture propagates spontaneously. In other words, a large β may disturb the initiation of dynamic rupture.

The problem of the constitutive law is still under active investigation. The background physics and the scaling relation in both space and time need to be clarified.

5.3 Complex Fault Geometry

The principal reason for developing the BIEM has been to consider the effect of complex fault geometry on the dynamic rupture process. Geologists have pointed out the importance of fault

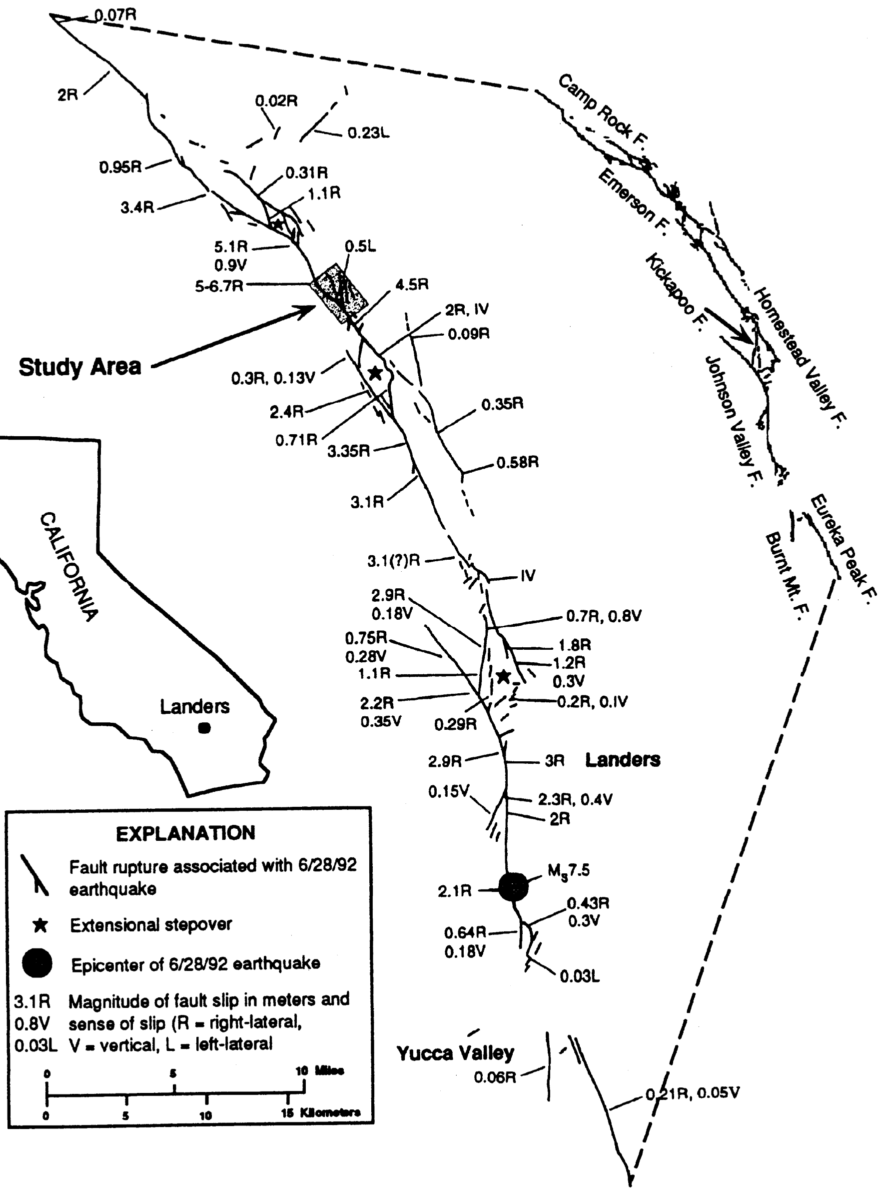


FIGURE 5.6 – Surface rupture of the 1992 Landers earthquake, originally observed by Hart et al. (1993) and redrawn by Aydin and Du (1995). Based on this observation, a non-planar fault model is constructed for dynamic rupture simulations (e.g. Figure 5.11).

geometry in rupture initiation and termination (King and Nabelek, 1985 ; Sibson, 1986 ; Shimazaki and Nakata, 1990 ; and many others), while seismologists discuss plane faults, with some exception such as Archuleta (1984) for the 1979 Imperial Valley earthquake. There had been previous numerical studies for non-planar faults using FDMs (Harris and Day, 1991, 1993, 1999 ; Kase and Kuge, 1998, 2000). However, the fault geometry is limited to a set of parallel or perpendicular segments according to the restriction of the FDM grids. In this point, a series of BIEMs has the advantage of flexibly treating fault geometry such as bending or branching (2D cases : Koller et al., 1992 ; Tada

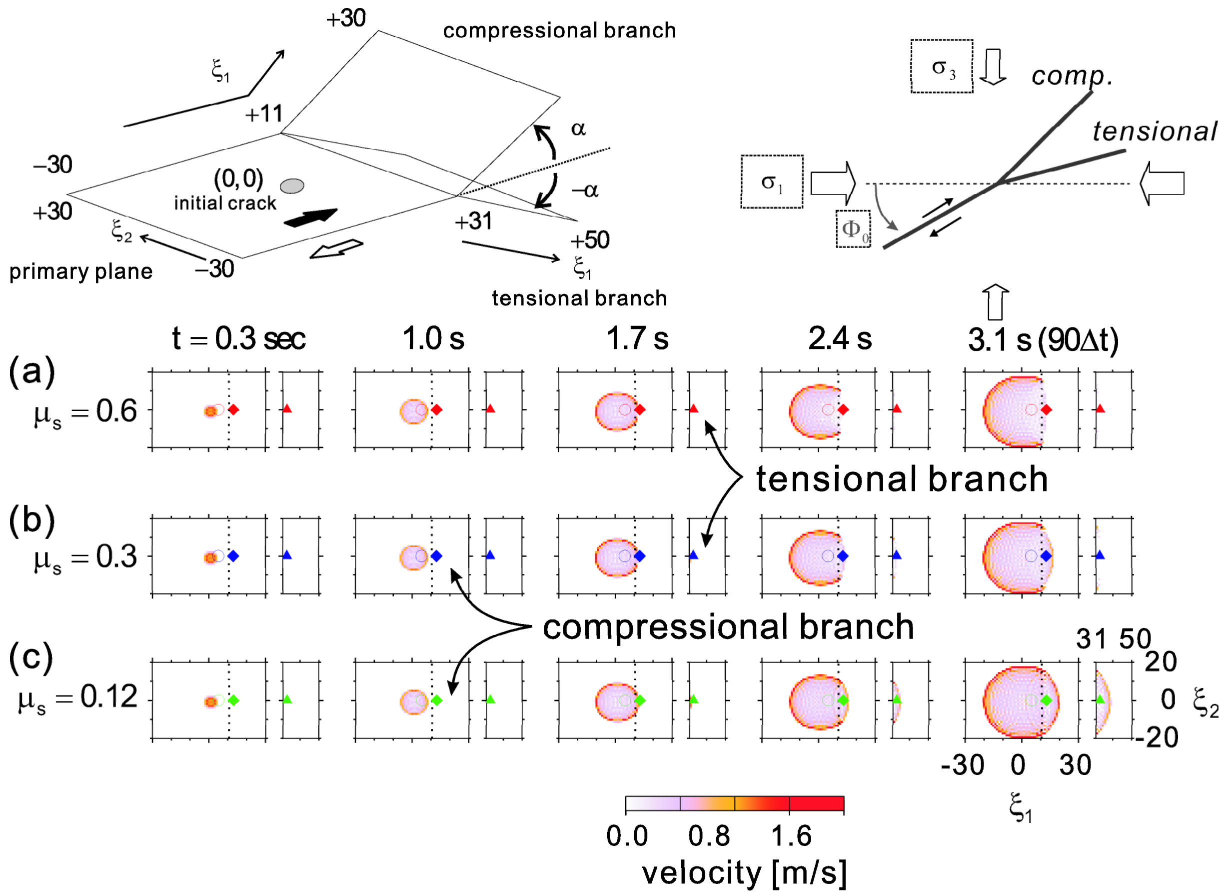


FIGURE 5.7 – Dynamic rupture simulation along a Y-shaped branched fault. The top panels show the fault's 3D view and its profile with respect to the external compressional forces σ_1 and σ_3 ($\sigma_1 > \sigma_3$). Here, fault geometry (branching angle α) and loading stress values are input parameters as well as the fault strength, namely frictional coefficients μ_s and μ_d. Assuming the same derivative stress condition (a rupture propagates in the same way on the primary plane), the dynamic branching features depend on the loaded stress on the branches. It should be noted that the rupture preferably progresses on the compressional branch (case b) and on both branches (case c). Stress evolution at the indicated points are shown in Figure 5.8. After Aochi et al. (2002).

and Yamashita, 1996, 1997 ; Kame and Yamashita, 1997, 1999 ; Bouchon and Streiff, 1997, Seelig and Gross, 1997). The 3D BIEM (Aochi, 2000) does not limit our discussion in general cases (Aochi et al., 2000a, b, 2002, 2005 ; Aochi, 2003) but we can discuss realistic situations that are found in earthquakes (Aochi and Fukuyama, 2002 ; Aochi et al., 2003 ; Aochi and Madariaga, 2003 ; Aochi and Kato, 2008).

The dynamic interaction as the rupture progresses is important in complex fault geometries such as curved faults, fault branching or segmentations. The favoring of crack curving is treated as spontaneous fracture progress in a 2D intact material, and proposed as a stopping mechanism

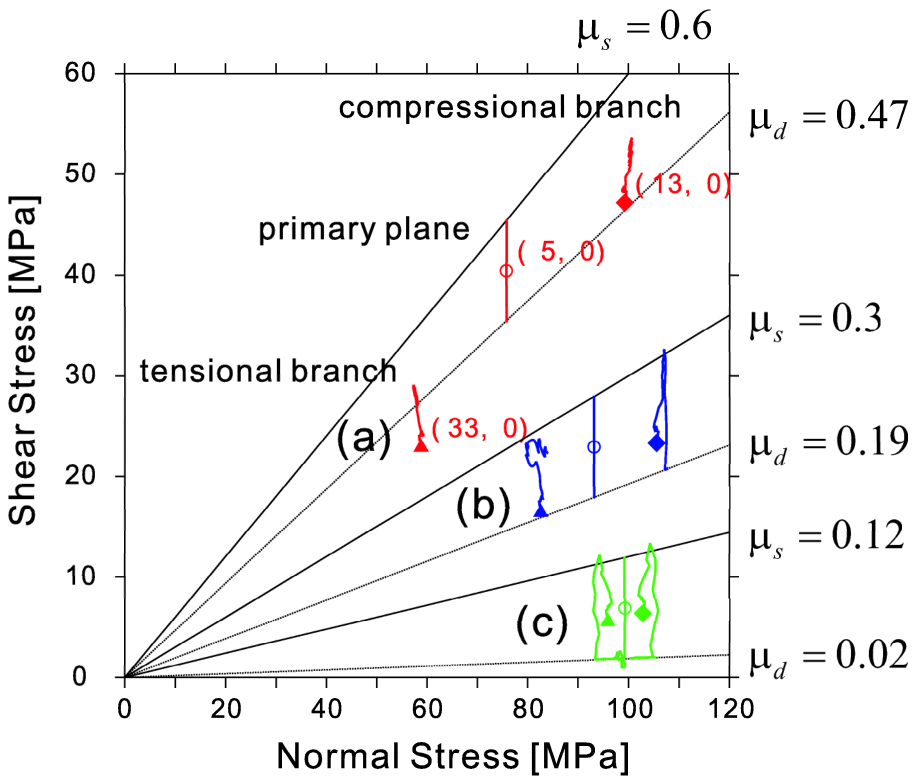


FIGURE 5.8 – Stress evolution at three points on each fault plane in the simulations shown in Figure 5.7. The symbols, representing the positions in Figure 5.7, show the initial stress condition. Regardless of the frictional coefficient values, the same derivative stress condition is imposed on the primary plane, namely 5 MPa and 10 MPa of static and dynamic stress drop. After Aochi et al. (2002).

for earthquake ruptures (Kame and Yamashita, 1999). In the case of pre-existing curving faults (geometry is given *a priori*), what happens as the rupture progresses ? This was first discussed in relation with the fault geometry and the external loading stress field, when I had developed the BIEM (Aochi et al., 2000). It should not be forgotten that we have to consider the absolute stress field unlike a planar fault where the deviatric stress (i.e. the change in stress during the earthquake) is sufficient. As a result, if a fault is weak (low absolute stress), the rupture can easily progress along a curving fault. In contrast, if a fault is strong (high absolute stress), the rupture is strictly limited to a planar geometry. This discussion is generally valid in the following studies of various fault geometry models, as will be explained in Figures 5.7–5.8.

A branching structure is also a fundamental element of fault geometries and it is curious to know to which direction rupture prefers to progress. The first case we studied is a plane fault with a branch segment (Aochi et al., 2000b). In order to only study the mechanism of dynamic interaction of rupture, initial stress condition and rupture criterion are uniformly given along all

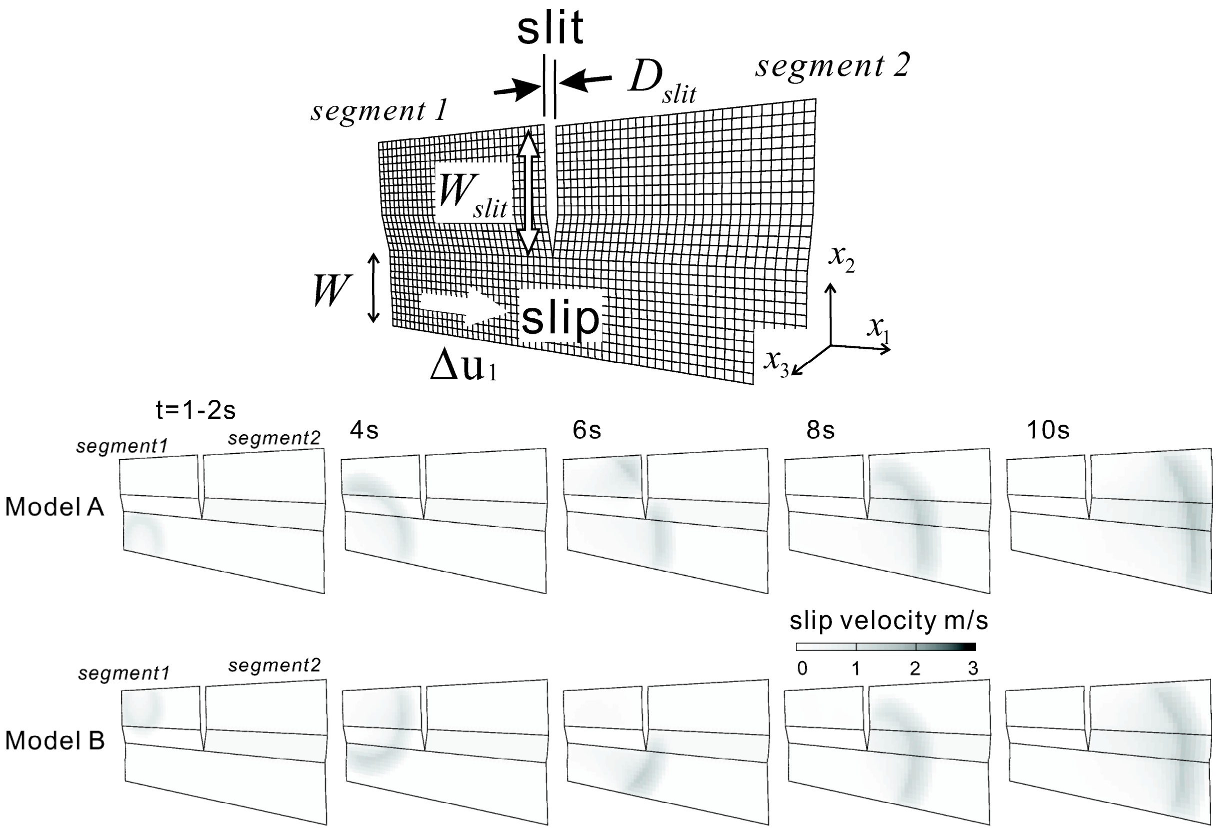


FIGURE 5.9 – Dynamic rupture simulation along a partially-segmented fault (top), which is in fact inspired by the prior simulation of the Izmit earthquake (Figures 5.17–5.19). The fault structure should be more complex at the ground surface than at depth. However, this simulation is conducted in an infinite medium. The two simulations (A and B) assume different hypocentral locations, clarifying the role of a slit and the continuity of fault segments. Slit width W_{slit} and length L_{slit} are 1.0 km and 7.5 km, fault width beneath the slit is 5.5 km. The slip weakening law is assumed without normal stress dependence (peak and residual strengths = 10 and 0 MPa, initial shear stress = 6 MPa, critical slip displacement = 0.5 m). Grid size 0.5 km, time step 0.045 s. After Aochi (2003).

the segments, neglecting any externally loaded stress field and any normal stress dependency on the rupture criterion. Two patterns are observed in the simulations : rupture progresses on both or either segment(s) beyond the branching point. If the branching angle is large, the two segments do not interact much. However, if the branching angle is relatively small, one of the segments is able to dominate the other because of the stress shadow effect. In this case the off-plane branch is sometimes preferred purely due to the dynamic stress perturbation caused by the branch. However, this is the case when external loading forces are neglected as are any stress fields surrounding the fault system. The normal stress dependency on the fracture criterion is studied in a Y-shaped branched fault as shown in Figure 5.7–5.8 (Aochi et al., 2002). In this case, the loaded stress varies with the segment orientation so that one has to discuss the delicate balance between the loaded initial stress and the dynamic stress perturbation. Let us assume that rupture initiates on the primary plane under a given compression stress field (Figure 5.7). Note that the parameters are chosen so as to initiate the rupture in the same way. One may think that the rupture progresses easily in the direction of least normal stress (tensional branch) through an analogy of Coulomb-type normal stress dependency. However, this may or may not be true. Figure 5.7 shows three situations with different frictional coefficients, namely different absolute stress levels. The rupture does not progress on the branches at all (case A), it propagates only on the compressional one (case B) or it propogates on both branches (case C). The result is very dependent on the given stress field, and its mechanics become clear when we plot the stress evolution for each segment (Figure 5.8). The loaded initial condition should be favorable enough to allow spontaneous rupture on the concerned segment. Both branches require the same shear stress excess to reach their peak strength. However, the compressional branch allows a positive stress drop, while the tensional one does not, as typically seen in Case B. This is what should be emphasized : high normal stress requires high yielding stress but also leads to high stress drop. Thus once rupture begins in a high normal stress regime, it can release much high energy.

Another interesting problem is the possibility of rupture transfer between segments. Figure 5.9 presents the dynamic rupture simulations in a partially segmented fault system (Aochi, 2003). Fault segmentations are inferred for many fault systems in the field. However, as demonstrated in the case of the 1999 Izmit earthquake (last section ; Figures 5.17–5.19, a smoother fault geometry can be sometimes seismologically preferred regardless of the fault segmentations geologically observed as surface traces. Therefore, Figure 5.9 is an analogy. The global feature of rupture propagation depends on the continuous part ; however, the detail differs due to the segmentation separated by a slit. Two simulations, shown in Figure 5.9, have different positions for the hypocenter. When rupture begins on the segmented part (Model B), it cannot jump from Segment 1 to Segment 2 across the slit so it must pass through the continuous part. This leads to a small change in rupture directivity and a time delay. I think that such mechanism must often occur in earthquakes. Aochi et al. (2005) study rupture transfer between different mechanisms. This is an analogy for active fault systems that consists of strike-slip faulting and reverse faulting. One needs a careful discussion of the initial stress field and the fault geometry. In any case, the applied initial stress must be favorable on each segment for rupture transfer to occur. The effect of different mechanisms of faulting appears in the rotation of the rake angle in the vicinity of the connection between the segments.

In this way, many simulations have been carried out for various situations to better understand rupture mechanics in non-planar complex fault systems. The examples listed in this section remain rather general. However, these experiences are applied (explicitly or implicitly) to the simulations of earthquakes (last section of this chapter). Recent progress has been made for dipping faults approaching the ground surface, using a hybrid method (Kame and Aochi, 2008 ; See Figure 4.7).

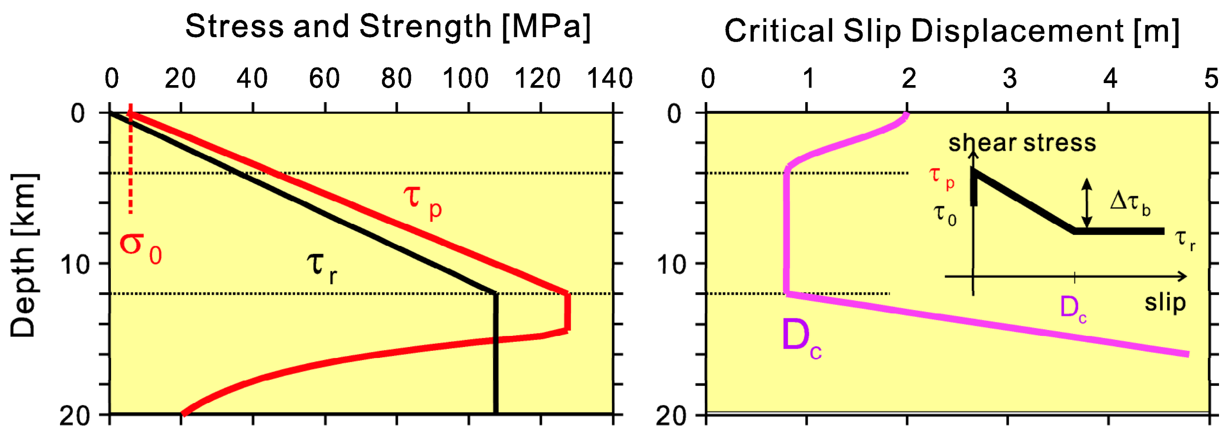


FIGURE 5.10 – An example of vertical heterogeneity in the fault constitutive law assumed in the simulations of the 1992 Landers earthquake and the 1999 Izmit earthquake (Aochi et al., 2003 ; Aochi and Madariaga, 2003). The increase in confining pressure with depth is taken into account in the peak strength τ_p and residual stress τ_r until a depth of 12 km and then the property turns from brittle to ductile, namely slip-weakening to slip-hardening (left panel). A finite cohesive force τ_0 is also assumed so that finite stress drop is possible at the surface. The critical slip displacement D_c considers the depth variation, with a stable regime in the shallow crust and at depth, inferred from the rock experiments and seismological inversion analyses. Figure after Aochi et al., 2003.

It should be noted that the effect of complex fault geometry on rupture dynamics is being constantly studied by different groups : through numerical simulations using the FEM (e.g. Oglesby and Day, 2001 ; Badea et al., 2008 ; Templeton et al., 2008), the SEM (Madariaga et al., 2006) and even by the FDM (Cruz-Atienza et al., 2007 ; Zhu et al., 2008). It seems that branching fault dynamics are especially important with respect to spray fault activation during mega-thrust subduction earthquakes. This should also be further studied by the BIEM and the hybrid method.

5.4 Fault Heterogeneity

The strength of any material, in particular, rocks is very heterogeneous. An earthquake fault should be very heterogeneous, as implied from inversion analyses of fault-slip mapping of numerous earthquakes. It is interesting to consider where such heterogeneity comes from physically. This is also an important element in the modeling of earthquakes.

Depth variation First a vertical variation (Figure 5.10) must exist according to the inevitable geological conditions, such as the increase in confining pressure and temperature with depth. The former effect is usually introduced in the dependency on normal stress according to Coulomb's law. The latter is introduced into fault parameters according to the material rheology. The rock rheology changes from brittle to ductile regime at a temperature around 350–400° C, corresponding to a depth of 12–15 km in the continental crust (e.g. Scholtz, 1990). This transition from an unstable brittle regime to a stable ductile regime is often described in terms of slip-rate dependency, such as velocity-weakening and strengthening, or as slip dependency, such as slip-weakening and strengthening or short D_c and long D_c. These give the same phenomenological results for a dynamic rupture process because the deeper ductile zone does not release stress so that there is no significant fault slip. There may be another stable zone in the shallow crust at a depth of less than 3 km where there is little seismicity. This interpretation is also possible from slip-rate dependency or slip dependency of fault properties. Such depth variation is often neglected in earthquake modeling but it should be taken into account even for dynamic rupture processes (Aochi and Fukuyama, 2002 ; Aochi et al., 2003). Furthermore the cohesive force, the fault strength near the ground surface, is hardly discussed in earthquake modeling. From a parametric study of the 1992 Landers earthquake, we found that the fault strength (cohesive force) must have been about 5–10 MPa even on the surface in order to release enough stress to obtain the observed large fault slip (Aochi et al., 2003). This question is also important to continue studying. An alternative question may be posed : why do some ruptures stop at a depth of several hundred meters without any surface rupture (the 2000 Tottori earthquakes) ?

Lateral variation and fault geometry Horizontal variation is more difficult to quantify. In the case of a non-planar fault system, applied shear stress varies according to the fault orientation (strike and dip) and the external stress loading direction. This can lead to a variation in yielding stress, if described by Coulomb's law. Is this sufficient ? What is also shown by Aochi et al. (2003), through the simulation of the 1992 Landers earthquake, is the macroscopic earthquake scenario (rupture area, rupture directivity, and large asperities) can be controlled by the heterogeneity generated by the non-planar fault geometry and the external stress loading, while additional heterogeneity is required in a detailed description to better explain the near-field waveforms (Figure 5.11). This indicates two perspectives for future research. Deterministic simulations under reasonable conditions will be able to provide possible scenarios of earthquakes and to estimate seismic hazard (later chapter). On the other hand, the heterogeneity at shorter scales requires some stochastic and statistic descriptions different from the deterministic one in order to explain the radiated seismic waves at high frequencies.

Heterogeneity and scaling law The heterogeneity problem is also related to rupture initiation and the scaling between small and large earthquakes. Rupture initiates somewhere from a weak point or from a point with high accumulated stress. As investigated previously in experimental, theoretical and numerical studies, rupture growth can be at first slow until the rupture size reaches a critical size L_c and then it accelerates. The size L_c is mechanically proportional to D_c and this

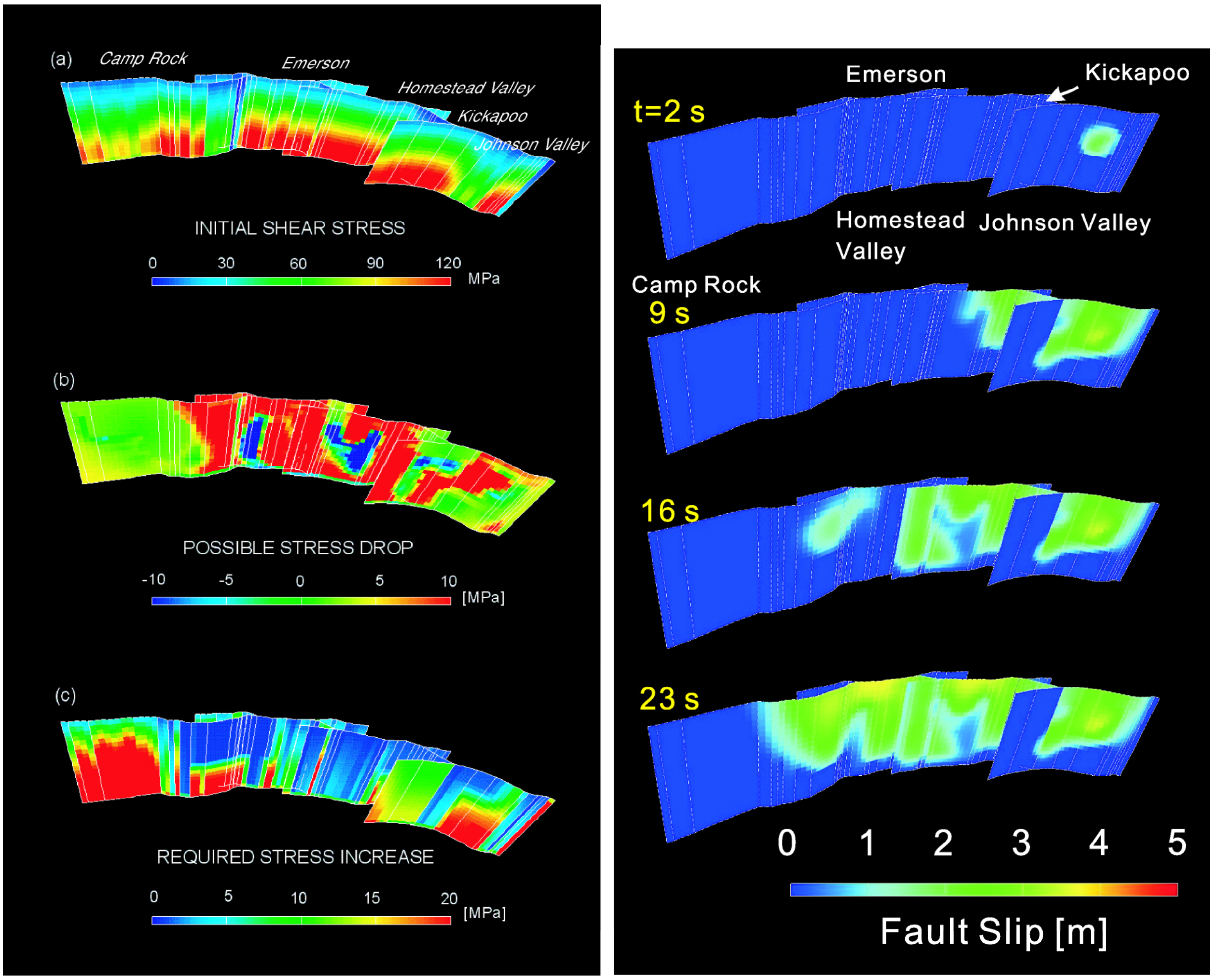


FIGURE 5.11 – The dynamic rupture simulation of the 1992 Landers earthquake after Aochi et al. (2003). (left) Initial condition mapped along the faults. (a) Initial shear stress produced by uniform external tectonic loading. (b) Possible stress drop, mapped from the planar-fault simulation. (c) Required stress increase obtained after adding the information in (b). This condition gives a better earthquake rupture scenario for explaining not only the macroscopic scenario of the rupture transfer segment by segment but also the waveforms in the near field. (right) Snapshot of the rupture progress during the simulation. See also Figure 5.16 for the subsequent ground motion simulations.

slows process in advance of the dynamic rupture phase known as "nucleation". This is in fact a key element on the predictability of forth-coming large earthquakes. If D_c really has the scale-dependency shown at the laboratory scale (micrometers) and in large earthquakes (a few 10 cm), it should be possible to detect the nucleation zone of large earthquake, as the nucleation size would be more than several km for a $M8$ event. Therefore, it is worth developing a dense observation network around potential earthquake source areas, for example, above the source region of the expected Tokai earthquake (more than $M7.5$). I think that the scaling between D_c, λ_c and L_c

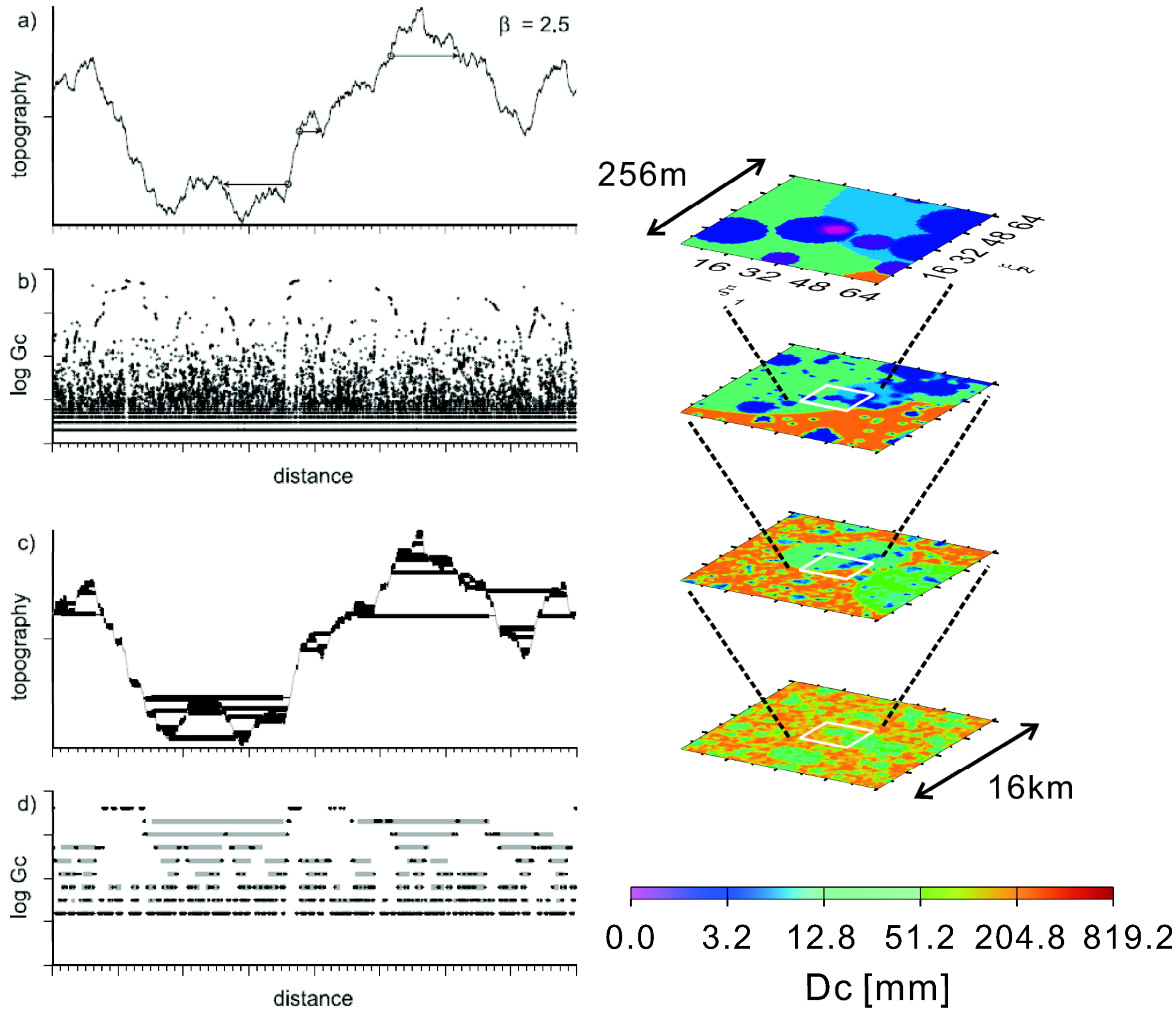


FIGURE 5.12 – Concept of the multi-scale heterogeneity in fracture energy G_c studied in Ide and Aochi (2005). The idea is consistent with the previous study in Figure 5.4. [Left] (a) 1D image of a self-affine topography. At each point (circle), the size of asperity is measured as the minimum length of the horizontal section (vector length). (b) Local G_c is proportional to the local size of asperities determined from topography. (c) An approximation of topography using a set of discrete line segments that obey power law statistics. Each segment is drawn at the tip of the asperity where the segment can fit. (d) Approximate G_c distribution (black dots) using the segment set (gray lines). [Right] An image of D_c distribution in two dimensions using a set of circular patches. We randomly distribute eight different orders of patches in 4096×4096 model space with periodic boundaries, which we consider to be 16×16 km. This model space is treated as four subspaces of different scales through three renormalization steps. A larger D_c appears to be dominant at a larger scale, but there exists numerous smaller D_c patches at smaller scales. After Ide and Aochi (2005).

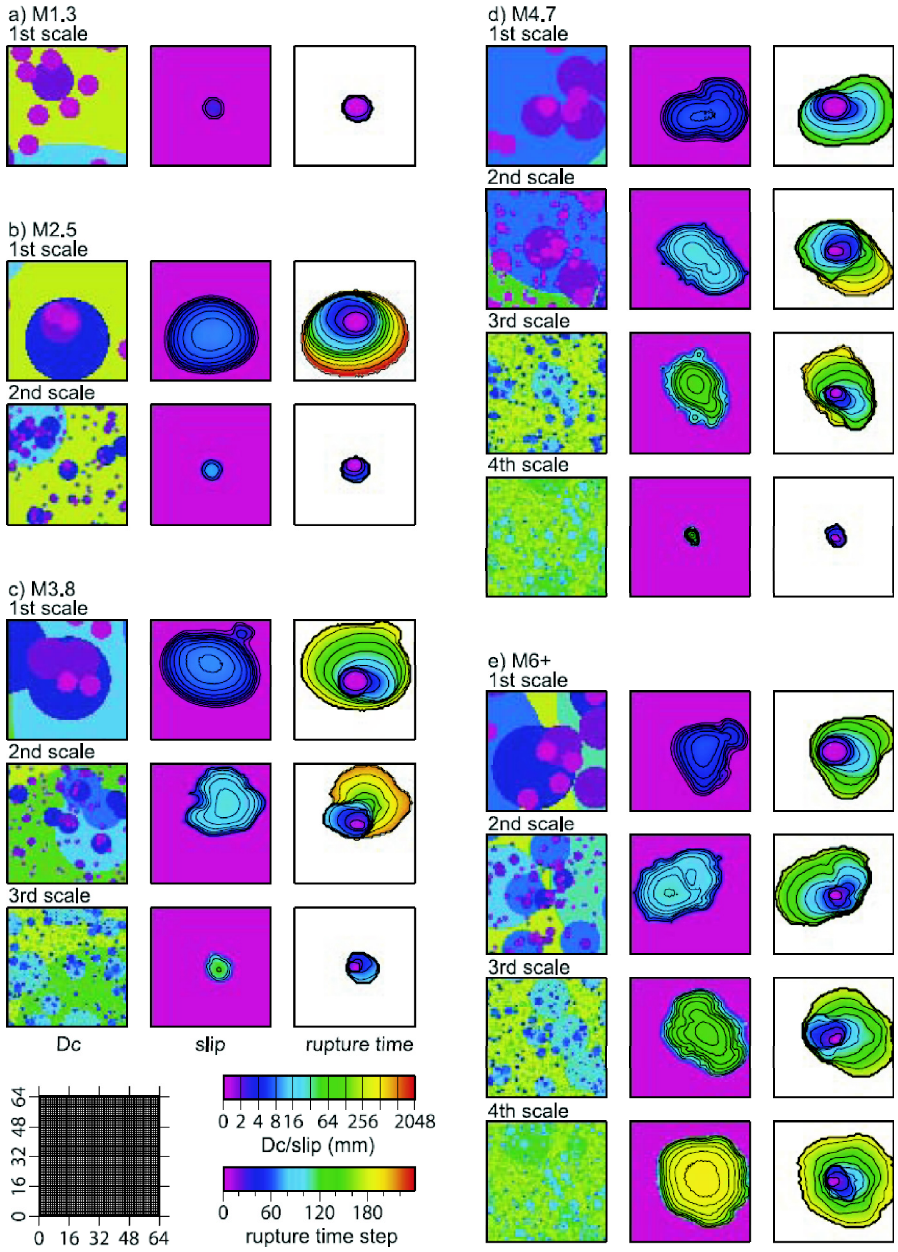


FIGURE 5.13 – Dynamic rupture simulation on a fault with the multi-scale heterogeneity shown in Figure 5.12. Regardless of the final event size (magnitude), all the ruptures are assumed to begin on one of the smallest patches, namely the weakest points. Each column shows the D_c distribution at each scale, fault slip at the last time step at each scale during the simulation and normalized rupture time. After Ide and Aochi (2005).

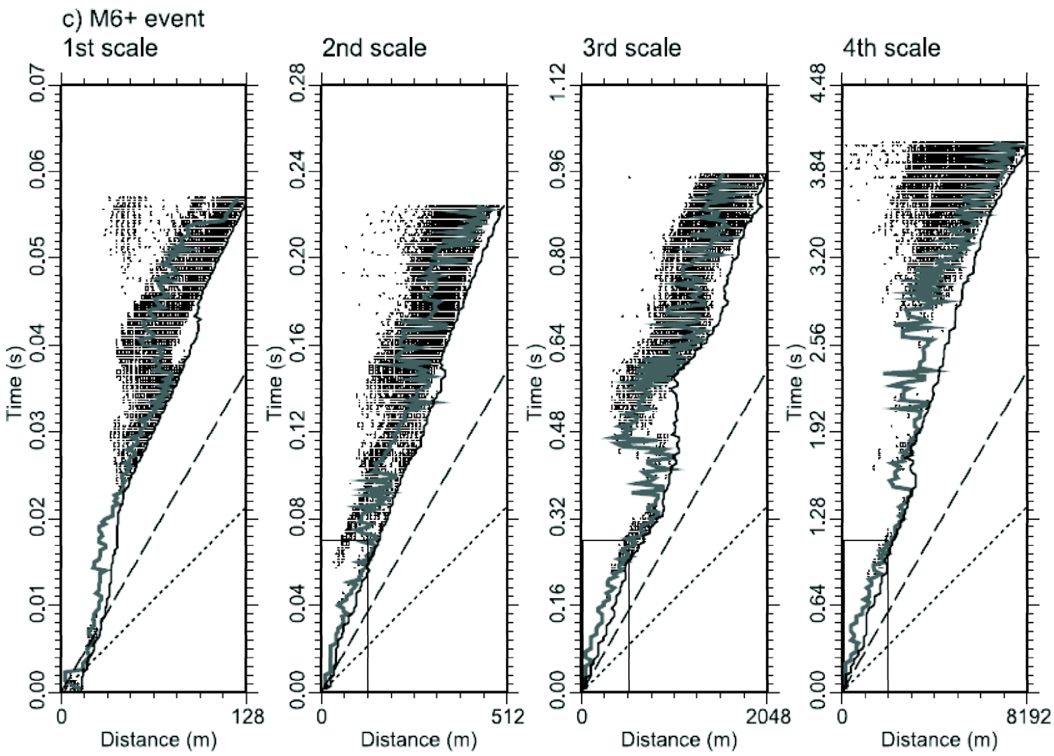


FIGURE 5.14 – The same simulation as for the biggest event shown in Figure 5.13. Thick solid lines show the location of the rupture front in space (distance from the hypocenter)-time plot. Gray lines represent the location of the maximum velocity. Dotted lines and dashed lines show the P- and S-wave velocities, respectively. Dots represents slipping area with slip rates faster than 25% of the maximum in each scale. Small rectangle box means that the previous scale is renormalized into the box. The rupture velocity is briefly constant at a velocity slower than that of the S-wave at any scale, while super-shear rupture is observed locally.

has been confirmed (Ohnaka, 2003). However, it is difficult to estimate D_c for earthquakes due to the resolution limit of seismological analyses. It is reported that D_c is about the order of 10 cm for earthquakes of a magnitude of around 7 such as the 1995 Kobe earthquake (Ide and Takeo, 1997) or the 1992 Landers earthquake (Olsen et al., 1997). Using the strong ground motion records observed very close to the ruptured fault, Mikumo et al. (2003) give a more reliable estimate of D_c, which is also of around 10 cm during the 2000 Tottori earthquake. All of my simulations reflect explicitly or implicitly this concept (Aochi and Fukuyama, 2002 ; Aochi and Madariaga, 2003 ; see also below, Aochi and Ide, 2004 ; Ide and Aochi, 2005).

There may be objections against this scaling. As nucleation size becomes a few km for $M7.5$–8 earthquakes, how can small earthquakes occur under such a situation ? A series of heterogeneities in small D_cs may give the mechanical effect of a large D_c, namely a large D_c is not intrinsic but apparent (e.g. Yamashita and Fukuyama, 1996 ; Campillo et al., 2001). On the other hand, as shown in Figure 5.13, Aochi and Ide (2004) and Ide and Aochi (2005) think that the D_c scaling is an intrinsic quantity based on the fractal nature of the material, as mentioned previously. Aochi and Ide (2004) are able to numerically demonstrate the idea that D_c should be proportional to the hypocentral distance, which is initially proposed by Andrews (1976). This is necessary to keep the self-similarity (rupture velocity and slip velocity are constant) in earthquake rupture at any scale. It should be noted that scale-independent D_c expand the rupture as it grows large enough. Ide and Aochi (2005) integrate this idea to show how D_c can be proportional to the hypocentral distance by considering multi-scale heterogeneity as shown in Figure 5.12. This model consists of the following two assumptions. The number of patches obeys the fractal relation (many smaller patches and few larger patches), and each patch has a characteristic D_c proportional to its size. Rupture may begin naturally at a small patch where a small D_c is attributed. In this case, any rupture encounters a larger D_c as it grows. As a result D_c is proportional to the earthquake size and small earthquakes can occur on the same area as large ones. It is important that this model also demonstrates the cascade-like rupture growth (Ellsworth and Beroza, 1995) even under the assumption of scale-dependent D_c. All the earthquakes begin in the same way (Figure 5.13). In this hypothesis, the final rupture size is not predictable from the initial movement on a fault. Figure 5.14 shows the rupture features of a large earthquake at different scales. Rupture velocity is quasi-constant at sub-Rayleigh speed, while locally super-shear rupture is observed. This concept is then developed in seismic wave analysis to observe such a multi-scale rupture initiation process (Uchide and Ide, 2007). The model should be refined more, but this topic is inevitable when studying earthquake dynamics at various scales.

5.5 Towards A Seismic Cycle

In the previous sections, single dynamic events have been discussed. I change subject now to the migration of such events with time and also I discuss the seismic cycle. There are many numerical studies on this topic, most of which use a rate- and state- friction law (e.g. Lapusta et al., 2000) because of its wide validity from aseismic slip to dynamic phases during seismic cycles. Equation (5.2) is an alternative law, which is also applicable for any aspect of the seismic cycle (e.g. Figure 2.5). Hashimoto et al. (2006) and Fukuyama et al. (2006) succeeded in quantitatively modeling the interseismic period and the dynamic rupture events around the area of the 1968 ($M7.9$) and 2003 ($M8.0$) Tokachi Oki earthquakes in the north of Japan. Stress concentration is naturally reproduced around the ruptured area due to the fault geometry (3D curved surface according to subduction) and the rupture is reproduced in terms of hypocentral location and ruptured area. This is an example of the predictability of earthquakes through simulations.

By the way, most of these models have a fixed scale of view for the target, normally the largest characteristic earthquake in a system. No earthquake smaller than the element size of the simulation

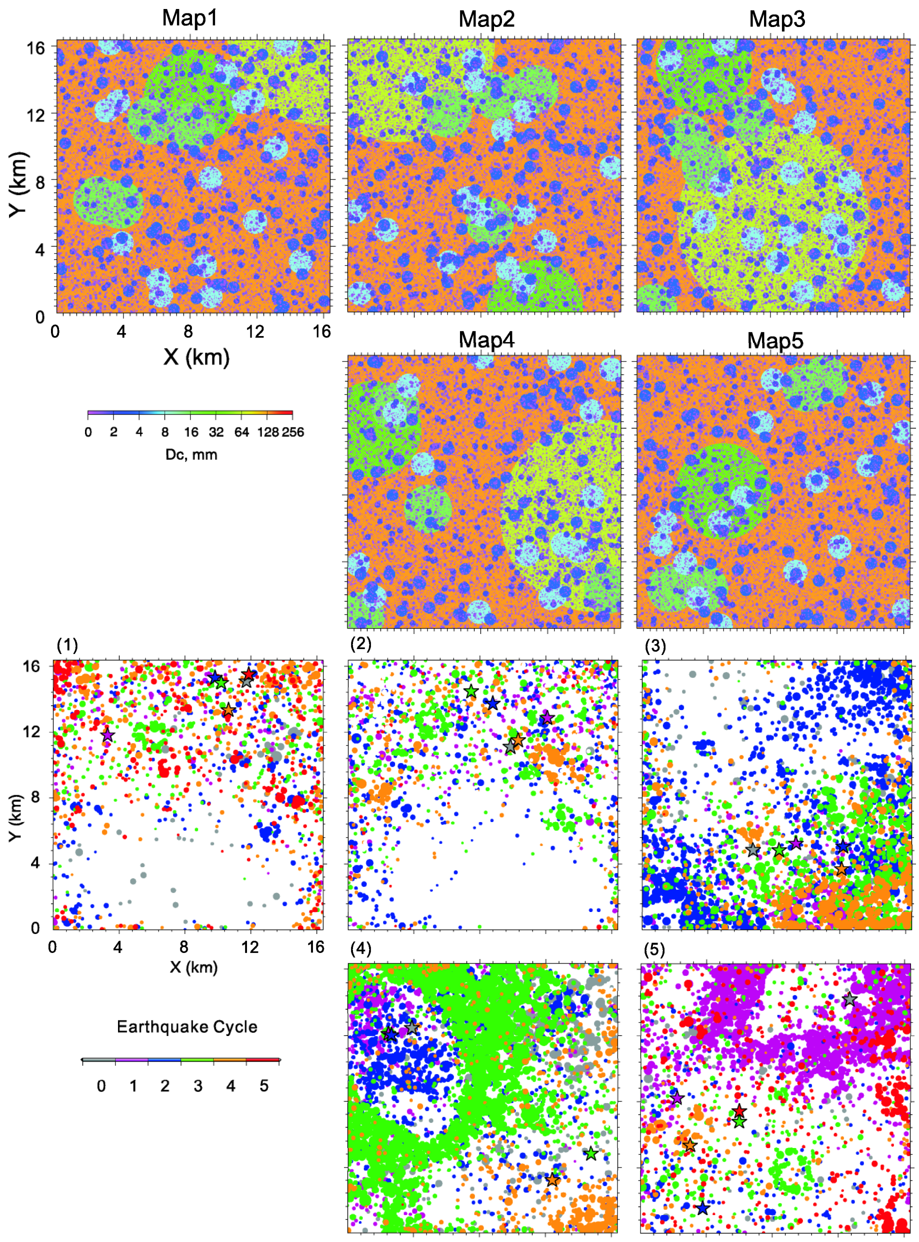


FIGURE 5.15 – Five fault heterogeneity maps at the top and the simulated seismicity during 100 years at the bottom (Aochi and Ide, 2008). Each point is a spontaneous dynamic event with finite fault size (the point size does not mean the physical ruptured area but it is proportional to event magnitude). Different colors represent each seismic cycle in which the characteristic event is marked by a star. In Models (1), (2) and (3), the characteristic events occur regularly in a similar way (hypocenter locations are close to each other). An abnormality is found in some cycles of Models (4) and (5). This is due to an intermediate event occurring during the cycle before the stress is sufficiently accumulated on the whole system.

is considered. The minimum earthquake size is required to be sufficiently larger than the element size due to the numerical resolution of the system of elastic equations (e.g. Rice, 1993). The system complexity can also come from the other parameters of the fault system such as fault segmentation, as seen in some recent studies (Duan and Oglesby, 2005 ; Shaw and Dietriech, 2007). However, as inferred in Ide and Aochi (2005), based on the multi-scale heterogeneity concept, any perturbations in smaller scale heterogeneity can accidentally lead to an important macroscopic phenomenon. Aochi and Ide (2008) simulate a series of dynamic rupture events during several seismic cycles on a fault with such multi-scale heterogeneities (Figure 5.15). Although the dynamic rupture process is deterministically simulated following the stress field and the fault parameters, its initiation process is stochastically described by random numbers. Namely, an event does not always start at the point where stress is accumulated the most. The event distribution varies spatially and some locations are possible if the initiation process has some dependency on the loaded stress around a point. From these simulations, many cases (Models 1, 2 and 3 in Figure 5.15) confirm the reproductivity of characteristic events. Namely they always begin with a similar area near a particular heterogeneity so that the global features of a dynamic event seem similar to one other. This is an example of when events are governed by existing fault heterogeneities. However, some seismic cycles show an anomaly (Models 4 and 5 in Figure 5.15). The characteristic earthquake happens differently in its nucleation position and its recurrence time. Such anomalies are not predictable in time but comprehensible from the given heterogeneity map. There is less connectivity of patches between the largest patchs or there is accidentally no largest patch. This is a good example of how the existing fault heterogeneity controls the seismicity and the characteristic events. Natural faults must be more complex and heterogeneous not only in fracture energy but in other parameters. However, this scaling idea of the fault properties could be the key to various problems.

5.6 Dynamic Modeling of Earthquakes

Although the studies presented in the previous sections are oriented to a general discussions on the mechanics of earthquake generation process, it should be recalled that the physical modeling of earthquakes is the main objective of this chapter. The methodology in 3D allows the modeling of some recent earthquakes and to compare them with observations. The inverse problem is not considered here because the dynamic process simulation is too expensive to investigate numerous parameters. I aim to show how close we can approach to the observations by fully physical modeling of the earthquake source. Nevertheless it should be noted that dynamic rupture simulation has become the objective of seismological inversions (e.g. Di Carli, 2008).

The first example shown here is from the 1992 $M7.2$ Landers earthquake. It is quite interesting to discuss the simulation results alongside the observational evidence. We have seen that the BIEM is a very powerful method for simulating the spontaneous progress of dynamic rupture during

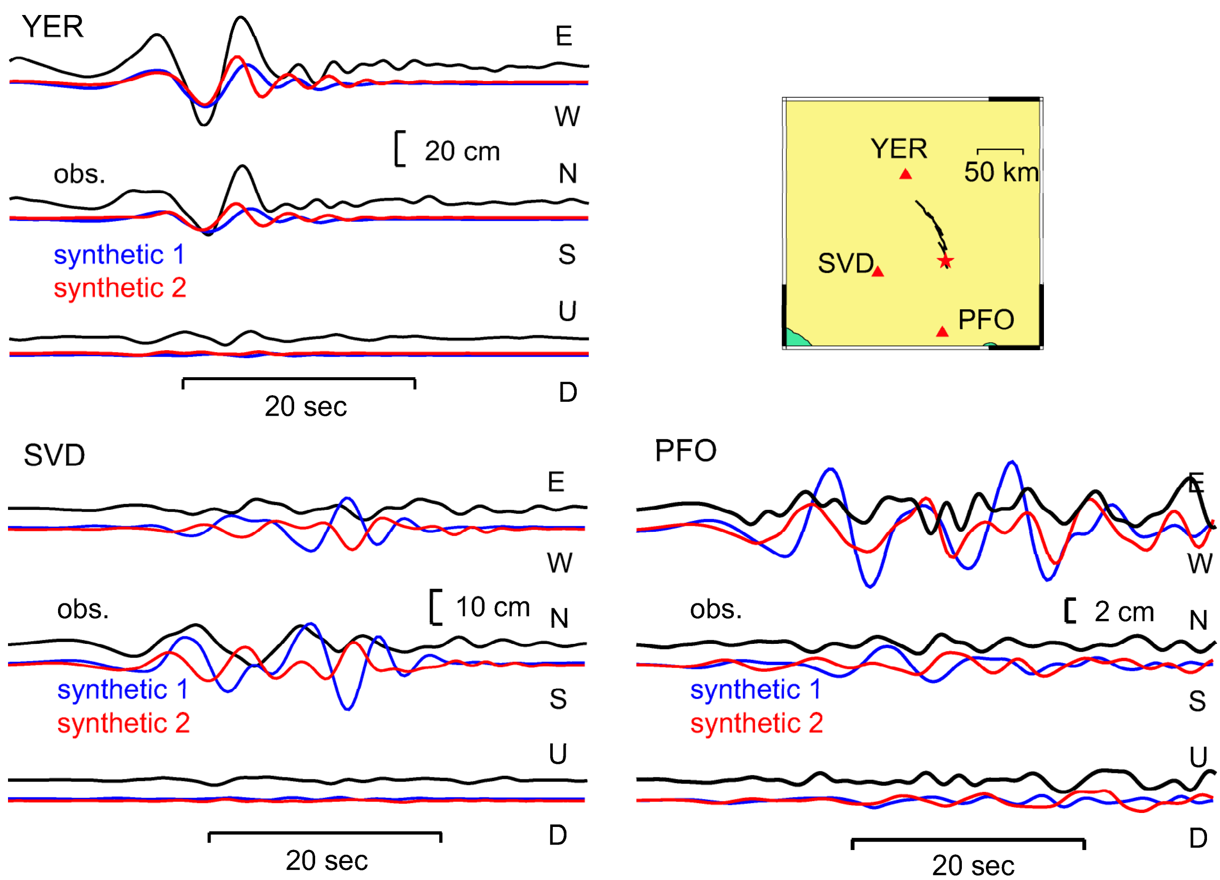


FIGURE 5.16 – Synthetic seismograms around the fault for the simulations of the 1992 Landers earthquake (Aochi et al., 2003). Displacement is filtered between 0.07 and 0.5 Hz. See also Figure 5.11 whose waveforms correspond to Scenario 2.

earthquakes, as already demonstrated in Figures 5.1 and 5.11 (Aochi, 2000 ; Aochi and Fukuyama, 2002 ; Aochi et al., 2003). Then the ground motion is calculated using a discrete wavelength method (e.g. code AXITRA) or the FDM (see the previous chapter). Figure 5.16 shows comparisons of the synthetic seismograms according to the dynamic rupture processes simulated for slightly different situations. The outer parameters such as the fault geometry and the tectonic stress loading briefly provide the main phases, such as a strong pulse due to rupture directivity at station YER (synthetic 1 in Figure 5.16, see also Figure 5.1). This assures that the correct rupture scenario at a large scale on the fault system is provided for a given situation. On the other hand, at the stations off the fault planes or behind the rupture direction, the amplitude is smaller so that detailed differences in waveforms become clearer. In this case some more lateral heterogeneity is required to reproduce the detail of seismograms (synthetic 2 in Figure 5.16, see also Figure 5.11).

The second example is, given in Figures 5.17–5.19, from the 1999 $M7.3$ Izmit earthquake (Aochi and Madariaga, 2003). Five different fault geometries are tested, as the ruptured trace was not

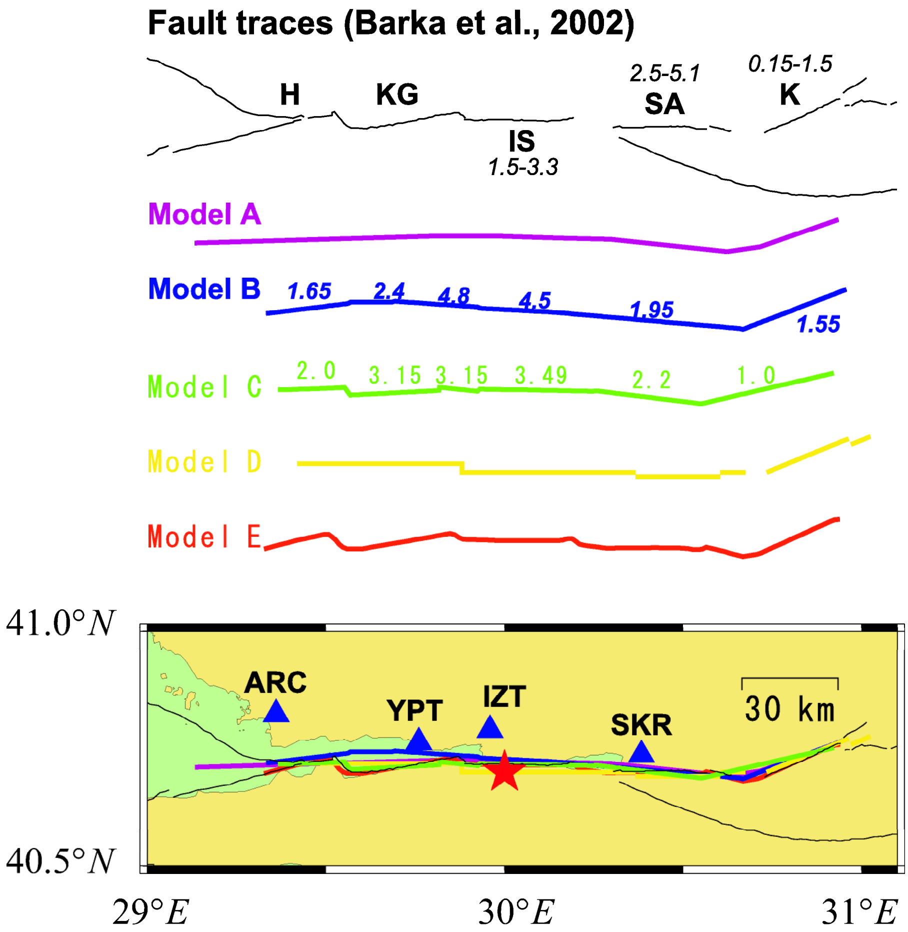


FIGURE 5.17 – Five fault geometry models simulated for the 1999 Izmit earthquake. From top to bottom : observed fault traces (Barka et al. [2002], whose observations results are numbered in meters), fault model A assumed in strong ground motion inversion (Bouchon et al., 2002), fault model B inferred from InSAR geodetic inversion (Wright et al. [2001], whose slip-model averages from two inversions are shown in meters), fault model C from SPOT image analysis (Michel and Avouac [2002], whose slip model in meters is also shown), fault model D used in the simulation of the FDM (Harris et al., 2002), and fault model E reflecting the observed fault traces shown at the top. At the bottom, we show the position of the fault and the seismic stations. The star represents the epicenter, and triangles show the seismic stations. After Aochi and Madariaga (2003).

always clear over the whole length of the fault system and different studies assume different traces according to the wavelength of their study. For the hypocenter area, we assume the same stress condition in order for rupture to initiate in the same way. Although the differences in fault geometry are small compared to the whole scale of this earthquake (Figure 5.17), the rupture process shows some significant differences. Let us compare two of the models in Figure 5.18. It is found in the western part that the change in fault strike disturbs the rupture's progress. In contrast, for the

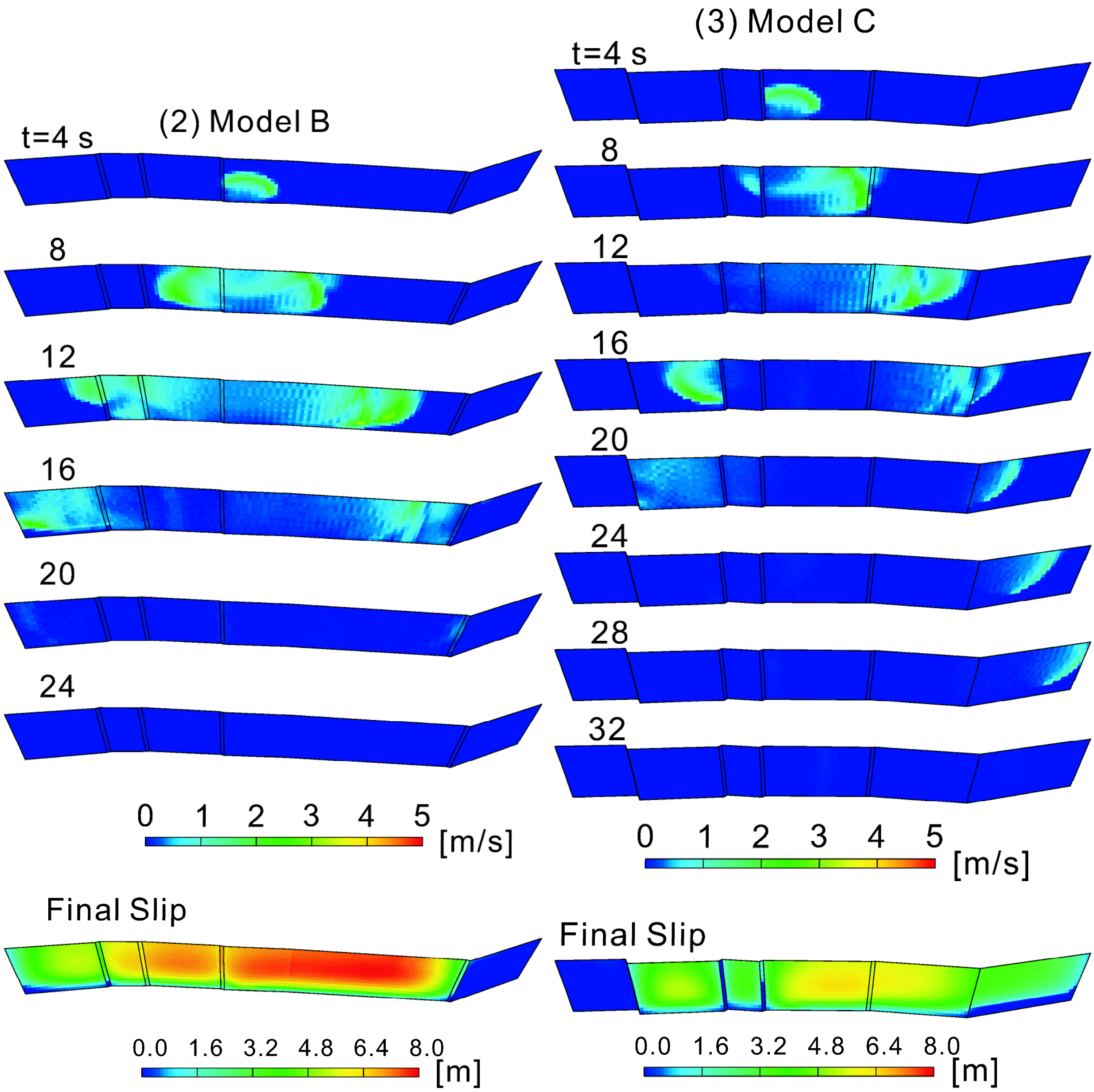


FIGURE 5.18 – Snapshots of dynamic rupture simulations for different fault geometry models, Models (B) and (C) whose geometry maps are shown in Figure 5.17. Small differences in fault geometry may provide significant difference in dynamic rupture scenarios even under the same stress condition. See also Figure 6.4 for near-field ground-motion simulations. After Aochi and Madariaga (2003).

eastern part, the rupture propagates very rapidly. This also causes differences in the near-field ground motion, later shown in Figure 6.4. Figure 5.19 compares the surface displacement between the simulations and the observations. The amplitude seems to be most consistent to model E while the spatial distribution pattern of surface displacements seems to be better in model B. This implies

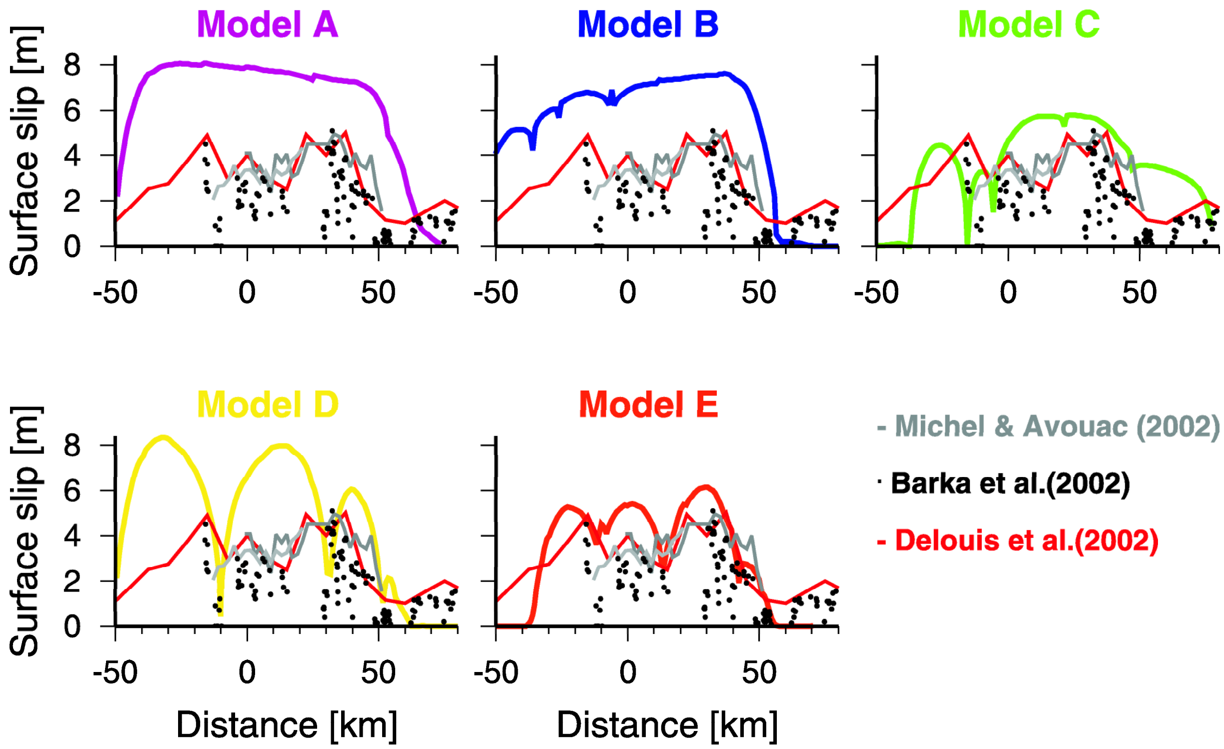


FIGURE 5.19 – Comparison of surface displacements along the fault trace for the 1999 Izmit earthquake. The tendency is close to Model B, but the amplitude is closer to Models C and E. After Aochi and Madariaga (2003).

that the complex local pattern is actually related to the segmentation of the faults observed on the ground surface, while the tendency at large scale is affected by the large scale deformation at depth, where the fault geometry should be smoother than in the shallow crust (e.g. Figure 5.9).

The subject of this section should be applied for many other earthquakes. In addition to the pioneering works from around 2000 cited early, some limited groups undertake such complex simulations. The FEM approach is powerful, as seen for the 1999 $M7.1$ Hector Mine earthquake (Oglesby et al., 2003) and the 2002 $M7.9$ Denali earthquake (Dreger et al., 2004). The FDM is has been applied for the 1999 Izmit earthquake (Harris et al., 2002). In addition, the BIEM is used for the 2003 $M8.0$ Tokachi-Oki (Fukuyama et al., 2006), the 2007 $M6.6$ Niigata-ken Chuetsu-Oki earthquake (Aochi and Kato, 2008) and others.

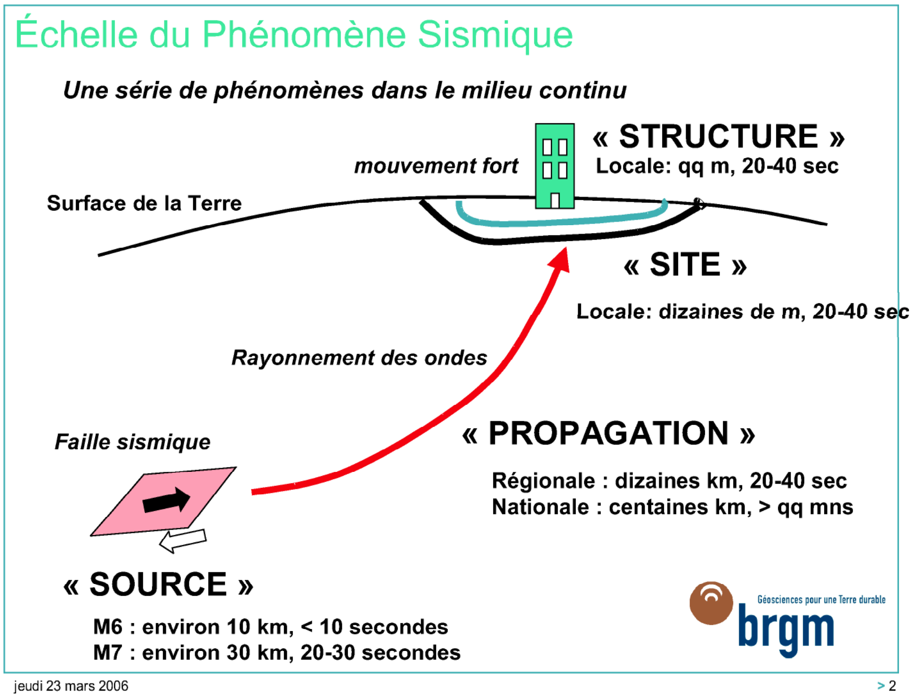
Chapitre 6

Application to Seismic Hazard Studies

6.1 Introduction

The most important practical contribution of the previous chapters is for seismic hazard studies. As encountered in the 1994 Northridge, the 1995 Kobe and recent large earthquakes, seismic hazard evaluation close to the earthquake source in a quantitative way is a matter of great urgency. In this case, we cannot assume a simple source model used in the far field. The damage zone around Kobe, away from the fault trace, was caused by the complex effect of the earthquake source, the wave propagation in the region and local site effects (Irikura et al., 1996). Source effects in near-field ground motion were remarked again as being important in recent earthquakes, such as the 2007 Niigata-ken Chuestu-Oki earthquake (Irikura et al., 2009). During the 2008 Miyagi-Iwate Nairiku earthquake, a strong-motion station above the ruptured fault recorded a peak ground acceleration of about 1 g at depth (4 g on the ground surface), which could be explained by the earthquake source. It is this domain to which earthquake source physics should contribute.

Interestingly, I had not begun on this topic before my arrival in France. My orientation to near-field ground motion is thanks to my work with Professor Raul Madariaga and the subsequent experiences at IRSN and BRGM. Figure 6.1 shows the strategy toward seismic hazard and risk evaluation (cf. Figure 5.1). Nowadays, each step is usually treated independently of other steps by simplifying the model parameters and the inputs. For example, for studying soil and structural response, the input ground motions are often simply given by standard methods or from a database. However, these cannot reproduce some destructive waves observed in recent earthquakes, so that the soil and structure responses are incompletely simulated. The final objective presented in Figure 6.1 goes beyond Earth science towards engineering. This is also an objective of the national project DEBATE (DEvelopment of Broadband Acceleration Time histories for Engineers), which begins in 2009. A complete series of the analyses described in Figure 6.1 are in principally possible, but the uncertainty in model parameters and scale differences should be carefully treated from one



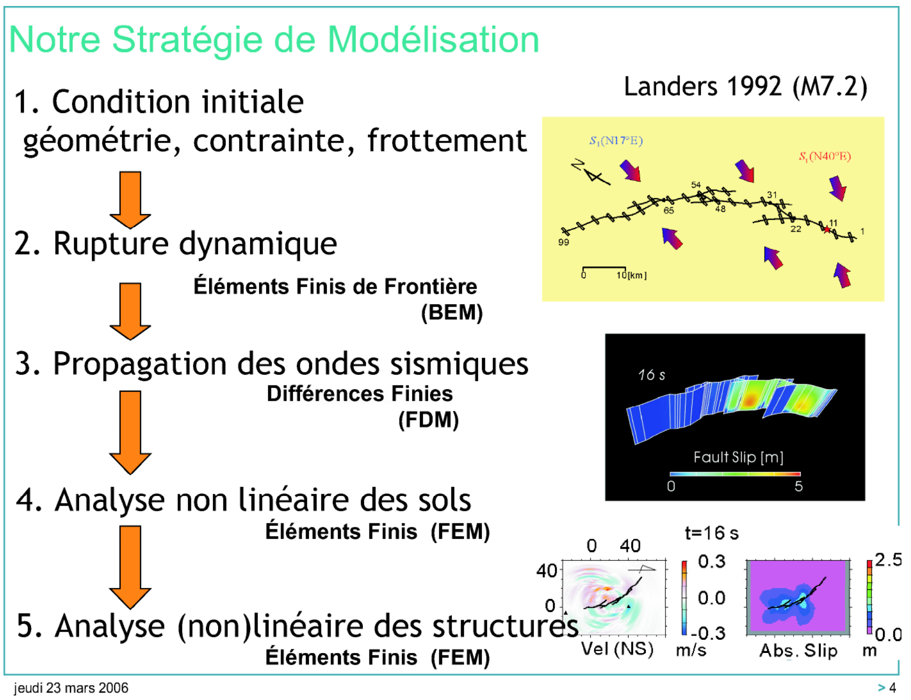


FIGURE 6.1 – [Top] Schematic illustration explaining the concerned scales of each step of an earthquake (earthquake source, wave propagation in the medium, site effect as amplification and non-linear soil behavior and response of an exposed structure). Let us consider events of magnitude 6–7, so that at regional and local scales, the phenomena should be analyzed for a duration of a few tens of seconds. [Bottom] Illustration of the mechanically-based methodology for a complete series of earthquake phenomena, from earthquake source beginning with geological conditions, seismic wave propagation to (non-linear) dynamic soil and structural analysis. After a presentation in 2006.

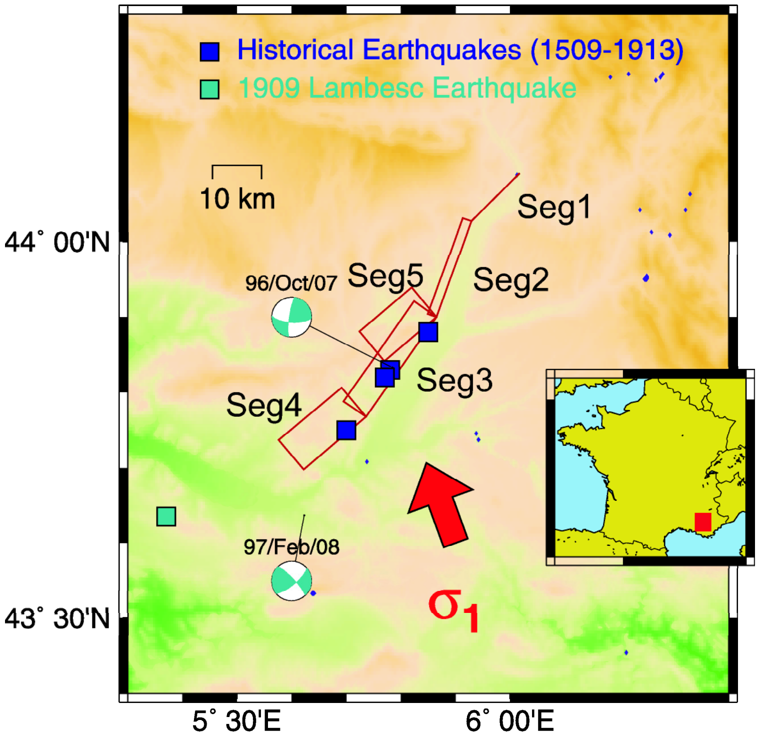


FIGURE 6.2 – Fault model consisting of five segments for simulating possible earthquake scenarios along the Middle Durance fault, France. (After Aochi et al., 2006)

step to another. The engineering topics presented here are team works within my institutes rather than my personal work ; this will be discussed later in Chapter 7. This chapter reviews, from my experiences, new contributions of the dynamic rupture simulations to the estimation of earthquake scenarios and the resultant strong ground motion in the near-field (seismic hazard).

6.2 Earthquake Scenarios

As reviewed in the previous chapter, it is important to note from the simulations of past earthquakes (Aochi and Fukuyama, 2002 ; Aochi and Madariaga, 2003) that the earthquake scenario (rupture directivity, rupture area, acceleration and deceleration of rupture and existence of large asperities) can be reproduced when we give reasonably realistic constraints on the fault geometry, fault constitutive law and external tectonic stress. It should not be forgotten that a small difference in fault geometry (kink, segment, or jog), which is not kinematically distinguished, plays a significant role in dynamic rupture propress.

At present, dynamic rupture simulation is able to be applied to estimate possible future earthquake scenarios in an active fault system, for example the Middle Durance fault in southeastern France (Aochi et al., 2006) (See Figure 6.2). Due to the uncertainty in model parameters, we carried

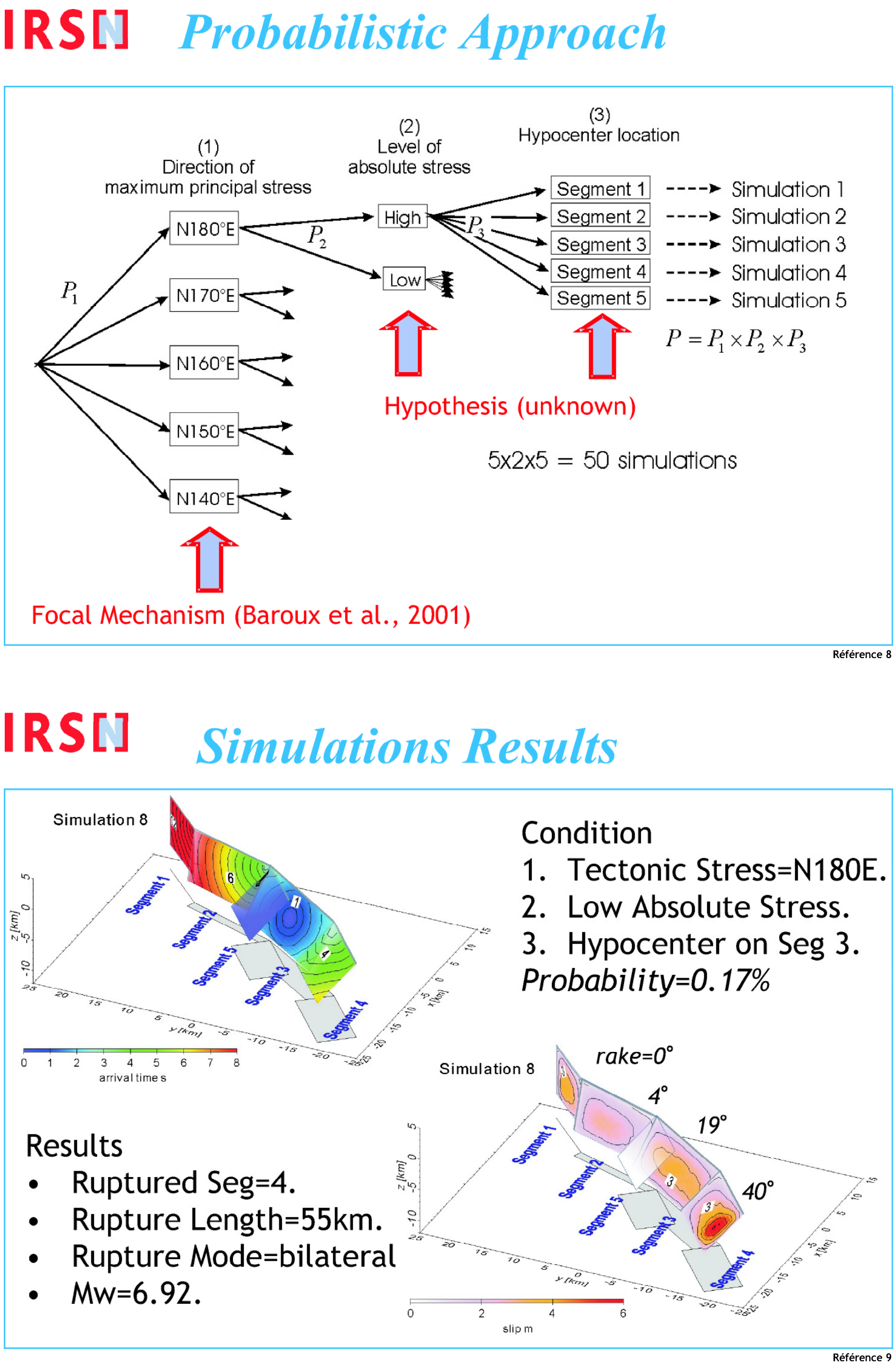


FIGURE 6.3 – [Top] Probabilistic approach for earthquake scenarios through dynamic rupture simulations. Three parameters are tested using probability laws. In total, 50 simulations were carried out. [Bottom] One scenario under a direction of tectonic stress of N180E°, a low absolute stress (weak fault) and a hypocenter on Segment 3. Figure shows rupture time and final slip distribution along a fault system. This scenario has a probability of 0.17% and finishes with a magnitude of $M6.92$. Figure after a presentation in 2004, integrated in Aochi et al. (2006).

out 50 simulations according to a logic tree, as presented in the top panel of Figure 6.3. The uncertain parameters are : 1) principal stress direction in this area, 2) absolute stress (strength) level applied on the fault and 3) hypocentral location. The simulation results allow us to statistically discuss the possibility of different earthquake scenarios. Which segment is likely to be broken in the fault system ? Which direction does rupture easily propagate ? How large is the expected earthquakes ? The procedure provides a probabilistic estimation of scenario likelihoods. An example of a scenario for the maximum magnitude is presented in Figure 6.3. This scenario, initiating from the northernmost segment, propagating southward over four segments and ending with a magnitude of 6.9, has a probability of only 0.17% among all the 50 considered scenarios. In this way, all the contributions from dynamic rupture simulations are important for quantitative seismic hazard study, although the numerical methods and the models should be improved and many other cases tested in future studies.

6.3 Strong Ground Motion

Simulating ground motions based on potential earthquake scenarios in a realistic geological context is a key issue for seismic hazard studies (e.g. Olsen et al., 1995). Wave propagation in a heterogeneous medium is the main problem for this objective. Furthermore, in the near field it is important to understand how the seismic waves are radiated from the complexity of the earthquake source. Before applying the approach for scenario earthquakes, it is imperative to study earthquakes with recorded data. The examples are given in the previous chapter together with dynamic rupture simulations (e.g. Figure 5.16, Aochi and Fukuyama, 2002). Figure 6.4 shows snapshots of ground-motion simulations for the 1999 Izmit earthquake (Aochi and Madariaga, 2003). It is visually very clear that strong wave pulses are associated with the rupture front. In fact, at SKR station, very close to the fault trace (see Figure 5.17), a very simple pulse on the EW component of ground velocity is recorded. This could correspond to the a simple passage of the rupture front around this location, as simulated in cases (2) Model B and (3) Model C.

As seen in Figure 6.4, the FDM is used in most of my recent studies because of its convenience. It should be noted that the discrete-wavenumber method (code Axitra) is also used for the earlier studies (Aochi and Fukuyama, 2002 ; Aochi et al., 2003) and for validating some numerical issues of the FDM. The discrete-wavenumber method has an advantage of precisely calculating seismograms up to high frequencies in a 1D-layered structure. On the other hand, the FDM allows us to volumetrically understand the wave radiation from the embedded source in a 3D-heterogeneous medium, although the discussion is limited to low frequencies.

One of the systematical studies of the relationship between the dynamic rupture process and strong ground motion is seen in Aochi and Olsen (2004), who study the effect of geometrical irregularity of a blind thrust fault, inspired by the 1994 Northridge earthquake. A small change of

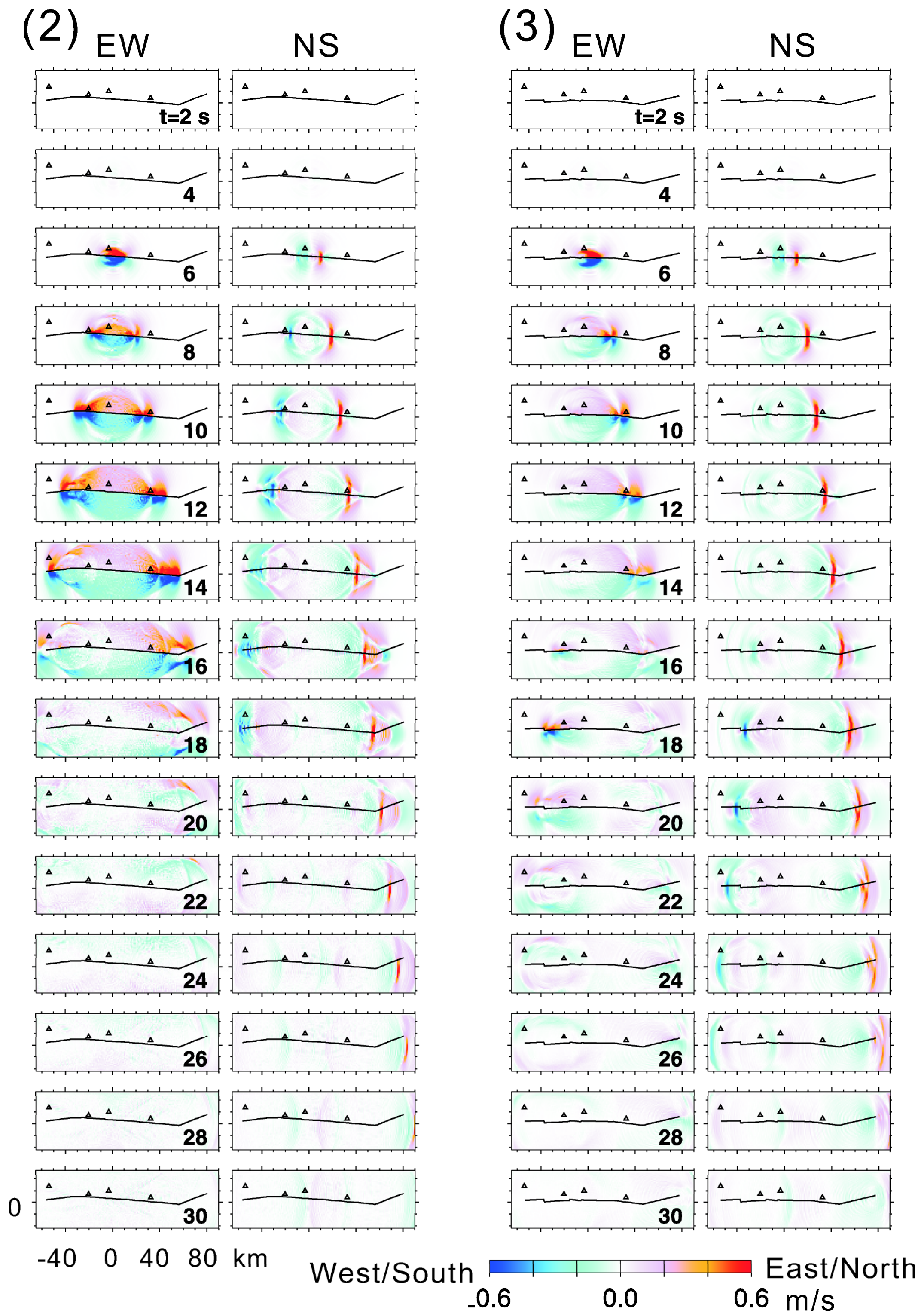


FIGURE 6.4 – Snapshots of the simulation of seismic wave propagation using the FDM using the dynamic rupture simulations presented in Figure 5.18. The strong pulse is associated with the rupture front. Triangles represent seismic stations. See also Figures 5.17–5.19. After Aochi and Madariaga (2003).

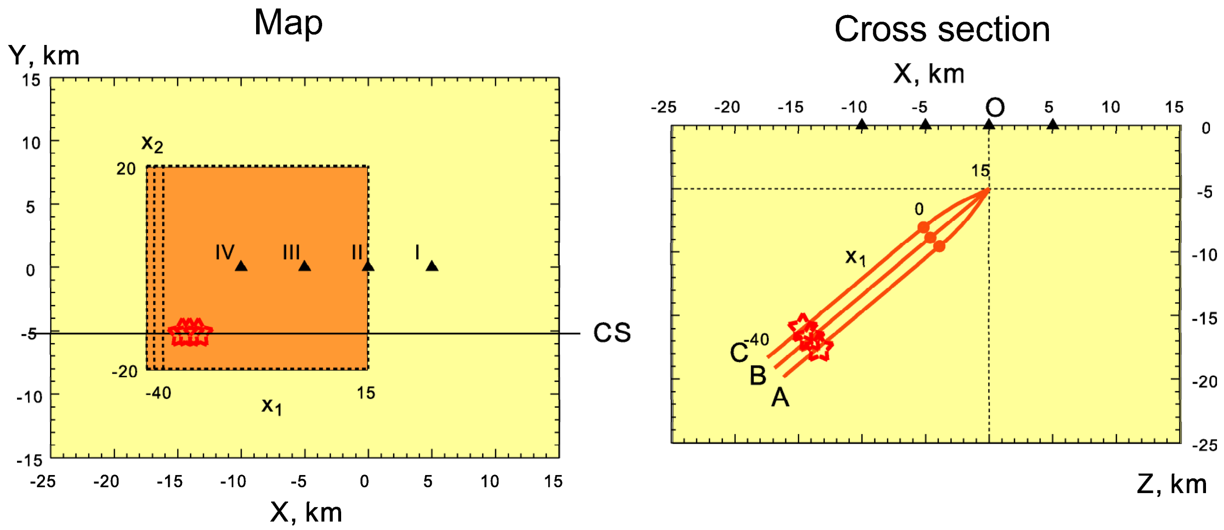


FIGURE 6.5 – Curved blind thrust faults inspired by the 1994 Northridge earthquake. Stars represent hypocenters. After Aochi and Olsen (2004).

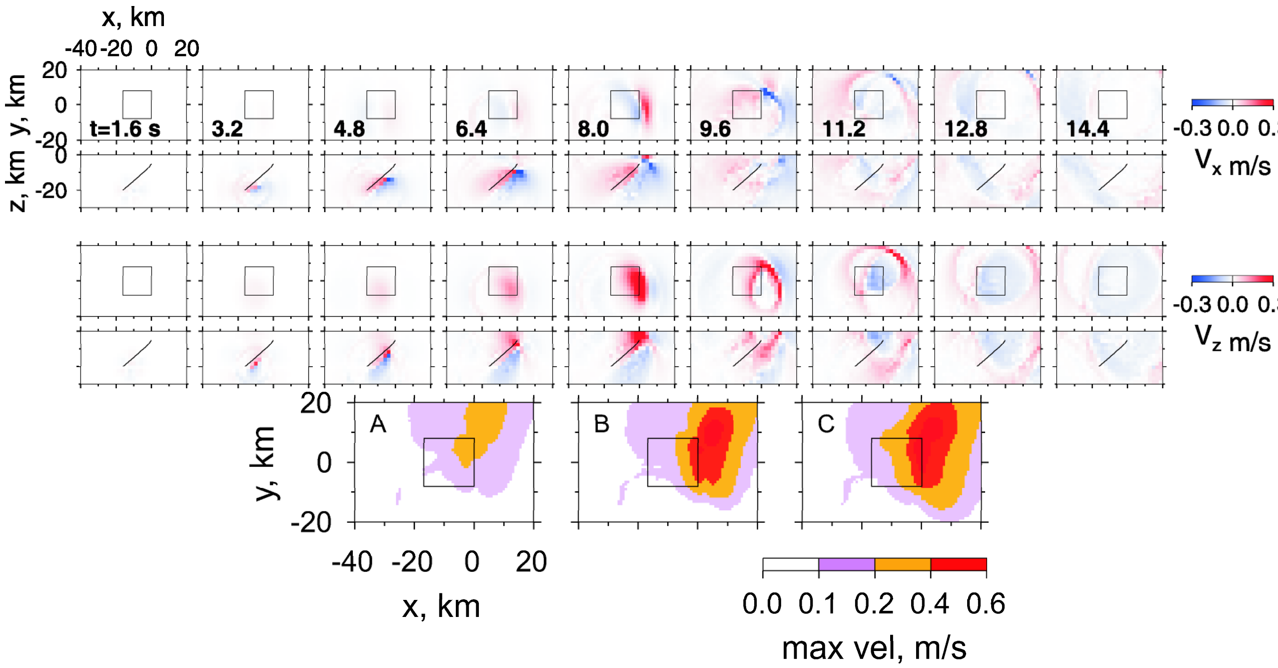


FIGURE 6.6 – [Top] An example of the seismic wave simulation for fault model A (Figure 6.5) using the FDM. The top and bottom panels represent horizontal (x direction) and vertical velocity fields on the ground surface and on a cross section (CS in Figure 6.5). [Bottom] Map of horizontal peak ground velocity according to three different geometry models. Note that the results include not only the kinematic geometry effect but also the dynamic rupture effect around the tip of the fault. After Aochi and Olsen (2004).

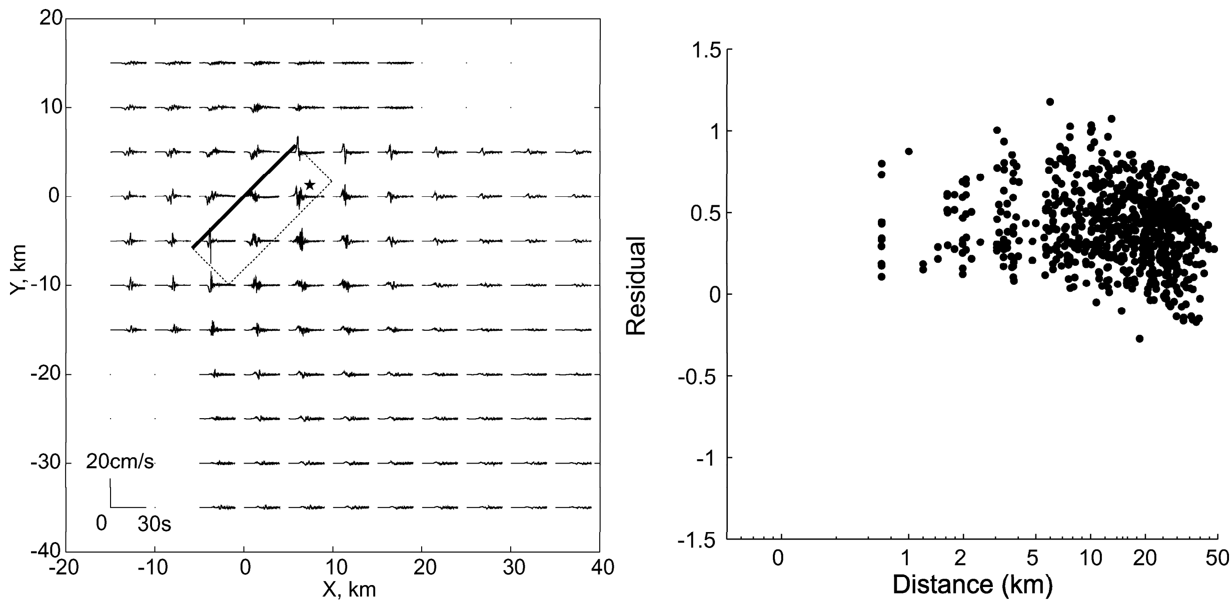


FIGURE 6.7 – [left] A wave propagation simulation (ground velocity in the Y component is shown) using the FDM based on the dynamic rupture scenario on a pure thrust fault simulated by the BIEM. [right] Horizontal Peak Ground Velocity (PGV) values for seven different earthquake mechanisms and scenarios with a distance to the fault. The vertical axis gives the residual with respect to an empirical ground-motion prediction equation (Campbell, 1997 ; 2000 ; 2001), defined by $\log 10(\mathrm{PGV}_{predicted} - \mathrm{PGV}_{simulated})$. Although there is nothing else than the dynamic source effect on a finite fault, the prediction varies by an order of magnitude. Figures after Aochi and Douglas (2006).

fault geometry (curve) close to the surface may accelerate, decelerate or stop the rupture progress so that the resultant ground motion is affected (See Figures 6.5 and 6.6). Although the fault is blind at a depth of 5 km, this difference in the termination process of rupture provides a factor of two in the peak ground velocity (PGV) according to the scenarios (fault geometry and stress field).

Ground motion in the near field is studied from another point of view. Aochi and Douglas (2006) and Douglas et al. (2007) compare the synthetic seismograms based on kinematic and dynamic rupture models with empirical ground-motion prediction equations often used in engineering (commonly known as attenuation relations). Many ground-motion prediction equations have been proposed for many engineering parameters, such as peak ground acceleration (PGA) (e.g. Douglas, 2003) and peak ground velocity (PGV), based on different data sets. These relations are very often used in engineering practice. However, there are few studies discussing the physics of such empirical equations to try to distinguish where the large observed uncertainties in the estimation comes from. An example is demonstrated in Figure 6.7 (Aochi and Douglas, 2006). The simulations show the strong effect of the earthquake source, which provides the same order of dispersion in the ground-motion model as observed in the recorded data. Empirical ground-motion models account for the source in a very simple way, generally by magnitude and faulting type. This observation leads to a new question : are seismic waves homogenized during their propagation and so obscure the complex source mechanism ?

Some examples of wave propagation at regional and local scales have already been shown in the previous chapters together with the development of numerical tools (e.g. De Martin et al., 2007 ; Dupros et al., 2008 ; Ducellier and Aochi, 2009). Studies for particular sites in France have also been carried out : Grenoble basin (Aochi et al., 2006 ; see also Figure 4.4), in the Antilles (Salichon et al., 2008), in the Nice region (Le Puth, 2005 ; Dupros et al., 2008) and in the Friuli region, north-eastern Italy (Imperatori et al., 2008). The simulation of wave propagation will remain a central axis of seismic hazard studies.

Chapitre 7

Perspectives scientifiques (Scientific Pespective)

Mes expériences au sein des différents organismes et à l'international depuis ces dix dernières années m'ont beaucoup servi en recherche et en ses applications. Il est important d'avoir des perspectives en tant que chercheur individuel et ingénieur d'organisme. Je vais d'abord résumer le projet de recherche dont je suis en charge depuis 2005 au sein du BRGM. En suite, je présenterai les perspectives de mes recherches individuelles : la recherche fondamentale sur le processus de la génération des séismes et la recherche appliquée sur l'aléa sismique dont certains éléments sont intégrés dans les propositions de recherche.

7.1 Projet de recherche au BRGM (Research project in BRGM)

Le BRGM (Bureau de Recherche Géologique et Minière) (French Geological Survey) est un organisme public (http ://www.brgm.fr). Le risque sismique est un sujet aussi important que le mouvement de terrain et le côtier au sein du service Aménagement et Risques Naturels. Le programme de recherche est engagé par le contrat ETAT-BRGM. Dans le contrat quadriennal ETAT-BRGM 2005-2008, l'objectif R&D n°1 déclare clairement que

- les mécanismes de déformation doivent être appréhendés afin de mieux prévenir la plus grande partie des risques naturels, notamment sismiques.

avec les actions qui en découlent :

- assurer la structuration des connaissances et la modélisation des processus, et
- développer l'intégration des outils de simulation numérique

Pour répondre à ces objectifs, le projet visera globalement à doter le BRGM d'une chaîne complète d'analyses permettant de comprendre et de prévoir les mouvements sismiques forts et les déformations massives, tant au niveau des mécanismes de la source et de la propagation des ondes générées, et au niveau des effets résultant en surface.

Afin d'améliorer l'évaluation du risque sismique, il est nécessaire de modéliser les scénarios de processus de rupture sismique dans un système de failles actives importantes en combinant plusieurs facteurs : la connaissance de la sismotectonique, des mouvements forts à l'échelle régionale en milieux hétérogènes, l'amplification du sol et des phénomènes non linéaires pouvant être induits par les séismes. Tout cela nécessite une mise en place des outils et des méthodologies adaptées, l'association de la connaissance de la structure interne de la terre et des mécanismes complexes de déformation.

Trois catégories d'analyses peuvent être proposées pour l'évaluation des risques sismiques :

1. Prédiction des paramètres simples de la secousse sismique (PGA, PGV, Intensité, etc.) à partir d'équations empiriques.
2. Synthèse des mouvements forts à partir de bases de données acquises.
3. Analyses dynamiques complètes allant de la source à la réponse sismique des sols en surface.

Selon la catégorie d'analyse envisagée, les paramètres d'entrée risquent d'être nombreux ou compliqués et la compréhension des phénomènes nécessite une bonne connaissance des mécanismes impliqués. Surtout, les méthodologies utilisées doivent être en adéquation avec le niveau de quantification visé : par exemple, une méthodologie très complexe et quantitative n'est pas forcément adaptée pour fournir des résultats qualitatifs. Elle doit en revanche être suffisamment précise pour servir notamment les autorités dans leur prise de décision ou les concepteurs d'ouvrages de génie civil, etc. Actuellement, les deux premières catégories d'analyses s'intègrent bien dans une démarche opérationnelle, bien qu'il y ait encore des améliorations à apporter. La troisième catégorie d'analyse constitue un enjeu important de recherche mais en est encore au stade du développement pour les équipes nationales et internationales.

Il peut y avoir plusieurs façons de classifier les actions de recherche. En termes thématiques, elles peuvent être composées de la sismotectonique, la source sismique, la propagation des ondes, l'effet de site et la mécanique de sol et de structure. Autrement on pourrait les diviser en deux orientations : la compréhension du mécanisme de l'aléa, la prédiction de l'aléa dans la prévention du risque. Dans ce rapport je vais les aborder dans l'optique des observations et des modélisations, en les associant avec mes recherches individuelles. Dans cette session, je citerai essentiellement les travaux effectués par le BRGM dans différents cadres.

Observation

Vu le statut du BRGM, l'observation de la terre en géologie et en sol superficiel est une mission principale, en plus il a l'avantage d'avoir toutes les cartographies. La structure géologique et la cartographie/classification des failles actives sont des composantes indispensables pour l'évaluation de l'aléa sismique. L'hétérogénéité du milieu et la géométrie des failles sont des paramètres principaux.

La cartographie digitalisée et la modélisation géologique (construction du modèle géologique) sont nécessaires dans la modélisation numérique à différentes échelles. Les données d'entrée sont souvent des profiles en 1D ou 2D basés sur la géophysique et par fois l'imagerie en 3D par la tomographie avancée. Chacune des données est indépendamment obtenue. En conséquent, il n'est pas évident de les combiner toutes dans un système cohérent. Le logiciel à modéliser la structure géologique 3D (e.g. 3D GeoModeller, http ://www.geomodeller.com) est un outil très performant, qui a lui-même le fonctionnement d'interpolation et d'interprétation (Calcagno et al., 2007). Il est actuellement utilisé pour modéliser la propagation des ondes à partir de la source sismique. La construction d'un modèle géologique performant et sa mise à disposition restera une des mes missions importantes au sein du BRGM. Par contre, ces modèles doivent être calibrés au travers de simulations. Il faut prendre en compte des incertitudes dans le modèle sachant que la résolution du modèle n'est jamais supérieure à la base de données.

En ce qui concerne les failles, il est important de comprendre non seulement la localisation et la géométrie mais aussi son historique et ses activités. L'évaluation d'aléa reste souvent stationnaire, mais la recherche envisagée dépend de la probabilité évolutionnaire par le temps de récurrence, le dernier séisme passé, le taux de déformation. Il nous faut également connaître la structure en profondeur des failles pour à la fois mesurer correctement la source potentielle et comprendre le mécanisme de la charge de contrainte sur des failles. Cela est lié à la question du mécanisme de la génération des séismes intraplaques (voir la session suivante). La base de données de séismes historiques représente un autre atout important. Les données acquises en France sont d'une homogénéité rare qui indique non seulement la localisation des séismes mais aussi l'intensité macroscopique par commune selon les documents historiques. Cela permet numériquement de simuler les séismes passés, par exemple, le séisme de Lambesc en 1909, afin de comprendre le phénomène et l'endommagement local. La modélisation numérique est comparable avec la cartographie de l'intensité macroscopique même si les données instrumentales n'existaient pas. (réf : Néopal, http ://www.neopal.net, SisFrance, http ://www.sisfrance.net)

La méthode géophysique que le BRGM développe est appliquée surtout au sol superficiel servant à l'aménagement et à l'évaluation du risque lié au sol. Pour le risque sismique, en particulier pour le besoin d'évaluer l'amplification du sol, la colonne de sol en 1D à partir de la base jusqu'à la surface doit être quantifiée (e.g. Roullé and Bitri, 2006 ; De Martin et al., 2008). Cette évaluation serait faisable à partir de la géophysique (source active ou fond de bruit) ou à partir des données enregistrées lors d'un séisme (voir aussi ci-après "modélisation").

L'observation des phénomènes permet de mesurer l'état actuel d'un séisme ainsi que son évolution. L'objectif est de collecter les données pour la recherche et de surveiller les phénomènes. Parmi les moyens employés, la télédétection par les satellites spatiaux est une méthode récente permettant d'observer la déformation à long terme sur la Terre. Comparée au GPS, il est certes dommage que les données ne sont pas en temps réel ni en continu (l'échantillonnage n'est pas fin), mais l'extension spatiale est très visible. Elle sert à détecter le mouvement de faille plus finement le long de la faille, comme le séisme de Sichuan en 2008 (e.g. De Michele et al., 2008a, 2008b)

L'autre mesure est basée sur les stations accélérométriques, capable d'enregistrer le mouvement fort sans saturation. Le BRGM fait partie de réseaux accélérométriques dans les Pyrénées, en Provence (RAP, http ://www-rap.obs.ujf-grenoble.fr, http ://www.brgm.fr/brgm/RAP/rap.htm) et aux Antilles (CDSA, http ://www.seismes-antilles.fr). Les stations semblent souvent soumises à l'effet de site (ex. le séisme des Saintes, aux Antilles, en 2004, Douglas, 2007 ; Douglas and Gehl, 2008 ; Salichon et al., 2008) et ne serviront pas encore à étudier la source sismique. La quantification de la caractéristique de chaque site et de son incertitude sera un sujet de recherche dans le futur.

Il existe deux autres sites (réseaux). Le premier, faisant partie également du réseau RAP, est une station installée à Belle-Plaine en Guadeloupe en profondeur et en surface. La station permet non seulement de détecter le mouvement sismique mais aussi les paramètres géomécaniques (pressions interstitielles) afin d'étudier le comportement du sol en site réel. Le site est sédimentaire liquéfiable et contient probablement beaucoup de fluide. Nous espérons enregistrer les données de séismes sur ce site prochainement. Le deuxième site fait partie du réseau ISARD dans les Pyrénées (http ://isard.brgm.fr) dont les stations sont connectées en continu en temps réel afin de localiser le séisme et d'estimer l'endommagement provisoire en temps quasi-réel. Tout comme d'autres systèmes similaires dans le monde entier, la fiabilité de la détermination au site devra être étudiée en calibrant et en optimisant le système en fonction du contexte régional.

Modélisation

A part l'observation, la modélisation numérique constitue un autre axe de recherche dans l'estimation de l'aléa et du risque. Ce processus est lié à la mécanique, mais il sert surtout aux fins statistiques ou aux observations.

L'extrait des informations par les observations est une méthode classique. La modélisation par des lois empiriques est globalement utilisée pour évaluer le mouvement sismique d'un séisme. Le choix de lois, plus précisément le choix de données, est essentiel. Ils déterminent une valeur moyenne et une variation, et cette variation est le sujet de notre recherche. Sans oublier que certaines données n'entrent pas dans cette régression et qu'aucune loi n'est adaptée en proche de source sismique (Douglas, 2003 ; Aochi and Douglas, 2006).

La modélisation d'aléa par approche probabiliste à partir de la sismicité fournit des résultats considérables dans le sens où la comparaison géographique semble possible. (e.g. Secanell et al., 2008). Elle reflète normalement la sismicité quotidienne : plus de séismes, plus de probabilité. Cette optique est tout à fait logique sous condition que les échantillons soient suffisamment riches dans cette base statistique. L'incertitude de cette modélisation peut être due à un manque de l'historique car le catalogue de sismicité instrumentale n'a que 100 ans et celui de l'historique ne dépasse pas

1000 ans. J'aborde encore cette question dans les sessions suivantes : les grands séismes récents notamment au Japon semblaient avoir eu lieu à l'endroit qui n'était pas surveillé, c'est-à-dire où il n'y avait pas eu beaucoup de séismes auparavant (fossé). La question reste ouverte.

La modélisation déterministe (basée sur la mécanique) est la principale partie de ma recherche et je l'ai déjà évoquée dans les autres chapitres. En plus, le BRGM est tenu de modéliser la dynamique du sol à échelle locale. Il est possible d'étudier l'amplification de sol en 1D par la matrice de propagateur et le comportement complexe lié à la géométrie ou à la loi de comportement par des méthodes d'éléments finis. Il est intéressant de noter que l'amplification des ondes en un site est différente s'il s'agit d'un séisme principal (mouvement fort) ou s'il s'agit des répliques (mouvement faible). Cela est déterminé par l'effet 2D, l'effet non-linéaire ou l'effet de la source sismique (e.g. De Martin et al., 2008). Le mouvement particulier du sol tel que la liquéfaction et l'étalement latéral est un sujet associé à ma recherche. Ici, le comportement du sol est lui-même discutable quand il devient à l'état particulier, très différent du milieu continu standard.

Pour le besoin ci-dessus, il est impératif de fournir les signaux d'entrée fiables. Sismologiquement parlant, un troisième type de modélisation basée sur la fonction de Green empirique est largement connu (e.g. Kohr-Sansorny et al., 2005). Il est très utile dans l'analyse du séisme qui a lieu dans l'endroit insuffisamment connu, à partir de ses répliques. Cependant, dans l'application pratique de l'étude de l'aléa sismique, il rencontre ses limites car cette méthode nécessite des enregistrements de séismes pour une paire de source et de site à étudier (mais cette hypothèse n'est pas toujours observée). Cela devient une contrainte en champ proche d'une source sismique comme le séisme de Niigata-Chuetsu-Oki en 2007, où les signaux par différentes aspérités sur la faille sont difficiles à reproduire.

7.2 Source Sismique (Earthquake Generation Process)

Dans cette section, je vais résumer la perspective sur la recherche de la source sismique. Le but final pourrait dans un certain sens être la prédiction des tremblements de terre. La possibilité de cette prédiction est à l'origine une question physique. En cas de réponse négative, il faut néanmoins comprendre la raison dans l'aspect "physique". Le terme "prédiction" est très vaste : où, quand, comment, quelle taille, etc. Est-ce suffisant de montrer un caractère statistique ou faut-il donner un scénario déterministe ? En tout cas, il faut comprendre que les tremblements de terre ont lieu en très grande échelle d'espace et de temps et ce fait crée un système très complexe qui est difficile à résoudre.

Je liste quelques questions générales :

– Comment la rupture sismique évolue-t-elle dans un système de failles qui sont déjà complexes ? Comment le tremblement de terre est-il influencé par la structure géologique existante, ou comment la rupture sismique forme sa morphologie ?

– Quel mécanisme apporte les différences d'échelle entre un petit et un grand séisme ? En terme du contenu fréquentiel, qu'est-ce qui différencie un séisme normal d'un séisme lent ?
– Comment le comportement de faille évolue-t-il pendant le cycle sismique ? Les paramètres tels que l'énergie de fracture sont-ils intrinsèques ou évolutifs ?
– Comment l'environnement tel que l'existence de fluide affecte le processus ?
– Comment la contrainte s'accumule et se relaxe non seulement dans une courte période cosismique mais aussi à long terme en interaction avec les autres failles et l'asthénosphère ?

Certains travaux ont été menés avec les collègues dans les projets de recherche. Ces thèmes sont toujours d'actualité (e.g. revue dans Aochi and Ando (2008)) et les collaborations se développent davantage. Les sujets principaux de mes recherches actuelles ou les idées de mes prochaines recherches sont par exemple les suivants :

– Comment la rupture sismique interagit avec la surface libre ?

Il y des travaux déjà réalisés notamment concernant le séisme de Chi-Chi en 1999 (e.g. Oglesby and Day, 2001), le mécanisme semble encore très complexe. Nous avons réussi à modéliser une faille inverse en 2D en développant une méthode hybride d'équations intégrales et de différences finies (Kame and Aochi, 2008a, b). Comparée aux autres méthodes, elle utilise des équations intégrales afin d'éviter des singularités fortes dans le problème. Notre étude récente montre que l'accélération de rupture est encore plus forte que notre supposition. Nous poursuivons notre recherche. Lors des récents séismes tels que le Wenchuen en Chine (M8.0) et le Miyagi-Iwate-Nairiku (M6.9) au Japon en 2008, nous avons constaté qu'une énorme énergie est libérée au-dessus de faille. Le mouvement sismique du séisme à M8 est-il différent d'un séisme à M7 ? Comment peut-on expliquer une accélération observée de 3800 cm/s^2 dans une composante verticale ? Cela rejoint l'aspect physique de recherche sur la source sismique et le mouvement fort en conséquence.

– Quelle serait l'hétérogénéité de faille ?

C'est un sujet de recherche classique, mais il faut avancer dans la compréhension de différentes échelles d'espace et des paramètres de dépendance. C'est important puisque ce problème d'échelle est lié au processus initial de rupture et au rayonnement des ondes pendant la rupture. Cette dépendance n'est-elle pas une propriété intrinsèque ? Ou est ce un effet mécanique suite à l'interaction mécanique (e.g. Campillo et al., 2001) ou la rhéologie microscopique autour de la faille (e.g. Andrews, 2005) ? Mes recherches sont basées sur la 1ere supposition : la dépendance d'échelle provient de la géométrie de faille qui a essentiellement une structure fractale en multi-échelle (Matsu'ura et al., 1992 ; Ohnaka, 2003). Les recherches en ce sens sont sur la bonne voie, je suis confiant que les différents aspects d'un tremblement de terre pourront trouver leur explication.

– Pourquoi les tremblements de terre ont-ils différentes échelles de temps ?

Les observations récentes ont découvert une série très intéressante de séismes (non volcanic episodic tremors, low-frequency earthquakes, very-log-frequency earthquakes, slow slip events and silent earthquakes) à une échelle de temps différent dans la subduction (Obara, 2002 ; Ito et al., 2006 ;

Shelly et al., 2006, 2007 ; Ide et al., 2007). Ces phénomènes sont étudiés par exemple par une loi "rate & state dependant" donnant différents valeurs sur le temps caractéristique (e.g. Shibazaki and Iio, 2003). Cependant il faut aller plus loin afin de comprendre l'existence de différents paramètres en large bande d'échelle. Il est à noter que cette sismicité est à ce jour trouvée dans certaines subductions mais pas systématiquement (le même réseau japonais Hi-net a pu détecter pour la plaque Philippine (sud Japon) mais pas pour la plaque Pacifique (nord-est Japon)). Comme indiqué dans les analyses sur la relocalisation des séismes et la tomographie, ce processus peut être associé aux déshydrations et à la circulation de fluide. Par conséquent, il faut introduire une description physique et chimique avant d'expliquer comment cette sismicité interagit avec un grand séisme.

- Comment la contrainte s'accumule et comment se relaxe-t-elle dans un cycle sismique hors de la période cosismique ?

J'ai commencé mes travaux par l'hypothèse où la contrainte est suffisamment accumulée dans un système de failles où la rupture dynamique peut se déclencher. Le séisme interplaque semble relativement simple à modéliser, parce que la plaine potentielle pour le grand séisme est clairement identifiée et l'historique des ruptures de cette interface est bien connu.

Quant au séisme intraplaque, il faut d'abord connaître pourquoi la contrainte s'accumule sur telle faille et pas sur d'autres. Ce sujet suscite toujours beaucoup d'intérêts et de discussions. Par exemple, Shimazaki and Triyoso (2007) ont conclu que la carte de taux de déformation par la mesure GPS récent au Japon ne correspond pas à la sismicité des grands séismes observés durant le 20ème siècle mais à ceux d'il y a 200 ans ! !

Ceci montre un argument sur le mécanique complexe de la déformation de la lithosphère et l'asthénosphère. Mécaniquement l'effet rhéologique en profondeur ne doit pas être ignoré (e.g. Shibazaki et al., 2007).

- Le mécanisme du séisme "non-tectonique" est-il semblable ou très différent des autres mécanismes évoqués précédemment dans mes recherches ?

A travers ce document, je cite notamment de grands séismes d'origine tectonique. Par contre, les tremblements de terre peuvent avoir lieu dans la croute dans des contextes variés tels que la volcanique. Certains phénomènes superficiels comme le mouvement de terrain peuvent aussi induire des tremblements de terre ; l'injection de fluide ou de gaz peut provoquer la sismicité, un séisme peut entraîner une autre sismicité à distance. On retrouve l'origine physique à travers tous ces faits. Les facteurs environnementaux (fluide, par exemple) pourront y jouer un rôle important.

7.3 Aléa Sismique (Seismic Hazard Study)

Un des objectifs finaux est de prévoir les phénomènes sismiques pour la prévention du risque en fournissant une méthodologie quantitative. Le développement des outils numériques est aussi important que la compréhension du mécanisme d'aléa. Il est important de savoir qu'en dépit de certains aspects physiques, les ingénieurs sont avant tout à la recherche d'un moyen simple à pratiquer. Le transfert de notre savoir-faire de la recherche fondamentale vers l'application est une mission essentielle.

– Une seule méthode numérique suffit t-elle à simuler tous les aspects sismiques ?

Il serait idéal d'avoir une seule méthode. Mais en pratique, il faut toujours adopter la méthode la plus adaptée selon les contextes, les besoins de recherche (sujet déjà évoqué dans les chapitres précédents ; voir également une revue Douglas and Aochi (2008)). En plus, le phénomène sismique varie beaucoup en échelle. Donc les méthodes de type hybride restent aussi utiles en toutes circonstances. Une amélioration constante sur chacune des méthodes est nécessaire en termes de performance et de capacité.

– Peut-on répondre à la demande des ingénieurs : générer les accélérations en large bande de fréquence ?

A ce jour, il semble qu'il y a encore un gap entre la demande des ingénieurs et la réponse apportée par le sismologue. C'est un sujet important et permanent. Par exemple, les méthodologies suivantes sont couramment utilisées afin de prévoir le mouvement fort en large bande de fréquence (e.g. Irikura and Miyake, 2001) : 1) fonction de Green empirique, 2) description stochastique d'une source finie + calcul synthétique des ondes dans une structure 1D. Ils reflètent certains aspectes mécaniques de la sismologie, mais avec limitations. Dans ce cas, j'envisage plutôt une autre approche, la fonction de Green stochastique. Elle a été initialement développée pour le champ d'onde S à distance en imposant quelques paramètres qui caractérisent la forme et le contenu d'onde (e.g. Boore, 1983). La phase fréquentielle est aléatoire. Elle est donc utilisable en large bande de fréquence et elle peut facilement générer plusieurs signaux temporels. Il est possible de la combiner avec une autre méthode en différents bandes de fréquence (approche hybride). Mais on constate que les deux méthodes - déterministe et stochastique ne sont pas toujours cohérentes en termes de phase notamment dans le cas où plusieurs phases de signaux sont visibles du à la complexité de source et milieu, c'est-à-dire en champ relativement proche. Il y a eu du progrès de développement vers l'ensemble des ondes. La description stochastique doit être consistante avec la déterministe en bases fréquences (Kagawa, 2004 ; Hisada, 2008). L'idée est de développer une méthodologie stochastique permettant une transition en douceur vers la stochastique en haute fréquence.

– Comment peut-on expliquer l'extrémité d'aléa ?

Les méthodologies standards pour l'évaluation d'aléa calculent toutes une valeur moyenne. Certaines prennent en compte une variation considérant des incertitudes de paramètres et des variations dans les données. Cependant l'extrémité des données qui est découverte souvent lors des grands séismes récents mérite aussi l'attention des chercheurs. Les extrémités de deux séismes ayant récemment eu lieu ont besoin d'être éclairées : Le séisme de Sichuan(Chine, mai 2008) est un séisme rare d'une magnitude 8 hors de subductions, enregistré par les stations accélérométriques dont certaines se situent tout le long de la faille. Le séisme d'Iwate-Miyage, Japon, en juin 2008, a enregistré une accélération d'environ 4 G (record mondial).

– Comment faut-il intégrer les observations dans la cartographie de l'aléa sismique ?

La méthodologie de prédiction du mouvement fort est en constante amélioration grâce à l'étude des séismes enregistrés aux instruments. Quant à la cartographie de l'aléa sismique, comment peut-on l'améliorer ? Dans le pays à sismicité élevée, la cartographie indique une probabilité à assez court terme (par exemple, 30 ans au Japon) et actualisé chaque année en prenant en compte l'évolution de la sismicité. La carte est réellement comparée aux enregistrements dans le réseau dense et homogène sur l'ensemble du territoire japonais depuis 10 ans (e.g. Fujiwara et al., 2007). Bien que certains grands séismes n'aient pas forcément eu lieu dans l'endroit à haute probabilité sismique, la surface totale soumise au mouvement correspond globalement à l'indication dans la carte. C'est un bon début de discussion entre la réalité et la prédiction.

7.4 Conclusion

Mes expériences dans les organismes publics français (IRSN et BRGM) m'ont fait comprendre l'importance de la recherche fondamentale et son application telle que l'évaluation de l'aléa et du risque sismique. Ces deux axes de recherches doivent être menés en parallèle et en continu.

Le développement numérique est essentiel dans les différentes applications. Il permet aussi une meilleure compréhension du processus de la génération des séismes pour lequel la conception du modèle et la compréhension de phénomènes sont fondamentales.

Je suis curieux d'approfondir le mécanisme de la rupture sismique, le rayonnement des ondes et la déformation. A la base, l'origine de cette curiosité est la volonté de comprendre la prédictibilité des phénomènes sismiques. Je souhaite contribuer à prévoir l'aléa sismique plus quantitativement, plus précisément et plus sûrement.

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Appendix

A Abstract of Papers

A.1 Aochi, H. and S. Ide (2008)

Complexity in earthquake sequences controlled by multi-scale heterogeneity in fault fracture energy

J. Geophys. Res. (in press)

A series of dynamic rupture events under constant tectonic loading is simulated on a fault with multi-scale heterogeneity and a stochastic rupture initiation process. The fracture energy of the fault plane is assumed to have multi-scale heterogeneous distribution using fractal circular patches. The stochastic rupture initiation process as a function of the accumulated stress is introduced in order to take account of unknown smaller-scale heterogeneity and variability. Five realizations of a statistical spatial distribution of fracture energy (fault heterogeneity maps) are tested for the simulations of earthquake sequences during a few seismic cycles. The diversity of earthquake sequences is principally controlled by the spatial distribution of the patches. The effect of dynamic rupture appears in the residual stress after the characteristic events due to their directivity and this localizes the subsequent sequences. Although the characteristic earthquakes occur rather regularly in time and similarly in different seismic cycles, some irregular behavior is found, based on the heterogeneity maps and the randomness of the preceding earthquake sequence, leading to a visible anomaly in the seismicity. Such anomalies are not predicable, but understandable through the analysis of the considered earthquakes during the cycle. The similarity and the diversity simulated in this study, governed by the structure of an inherent distribution of multi-scale heterogeneity, suggests the importance of the pre-existing heterogeneity field along the fault for the appearance of earthquake sequences, including those that are characteristic.

A.2 Aochi, H. and R. Ando (2008)

Numerical simulations on faulting : Microscopic evolution, macroscopic interaction and rupture process of earthquakes

J. Seism. Soc. Japan (in press)

We review the recent researches of numerical simulations on faulting, which are interpreted in this paper as the evolution of the state of the fault plane and the evolution of fault structure. The theme includes the fault constitutive (friction) law, the properties of the gauge particles, the initial phase of the rupture, the dynamic rupture process, the interaction of the fault segments, the fault zone dynamics, and so on. Many numerical methods have been developed : boundary integral equation methods (BIEM), finite difference methods (FDM), finite or spectral element methods (FEM, SEM) as well as distinct element methods (DEM), discrete element methods (again DEM) or lattice solid models (LSM). The fault dynamics should be solved as a complex non-linear system, which shows multiple hierarchical structures on its property and behavior. The researches have progressively advanced since the 1990's both numerically and physically thanks to high performance computing environments. The interaction at small scales is modeled to provide a large scale property of the fault. The dynamic rupture has been actively studied especially for the effect on the fault geometry evolution or due to the existed fault structure. The (quasi-)static and the initial processes of the fault movement have been also explored in a seismic cycle. The effect of fluid or heat has been also taken into account in the mechanics. All these efforts help us to understand the phenomena and the unified understanding (simulation) over different spacio-temporal scales is more and more expected.

A.3 Douglas, J. and H. Aochi (2008)

A Survey of Techniques for Predicting Earthquake Ground Motions for Engineering Purposes

Surv. Geophys., 29, 187–220

Over the past four or five decades many advances have been made in earthquake ground-motion prediction and a variety of procedures have been proposed. Some of these procedures are based on explicit physical models of the earthquake source, travelpath and recording site while others lack a strong physical basis and seek only to replicate observations. In addition, there are a number of hybrid methods that seek to combine benefits of different approaches. The various techniques proposed have their adherents and some of them are extensively used to estimate ground motions for engineering design purposes and in seismic hazard research. These methods all have their own advantages and limitations that are not often discussed by their proponents. The purposes of this article are to : summarise existing methods and the most important references, provide a family tree showing the connections between different methods and, most importantly, to discuss the advantages and disadvantages of each method.

A.4 De Michele, M., D. Racoules, H. Aochi, N. Baghadadi and C. Carnec (2008)

Measuring coseismic deformation on the northern segment of the Bam-Baravat escarpment associated with the 2003 Bam (Iran) earthquake, by correlation of very-high-resolution satellite imagery

Geophys. J. Int., 173, 459–464, 2008

The role that the oblique reverse fault projecting to the surface at the Bam-Baravat escarpment (BBE) played in the slip accommodation of the 2003 (Mw 6.5) Bam earthquake is still unclear, regardless of many seismological and geodetic studies following this event. In this study, we correlate pre- and post-seismic very high spatial resolution panchromatic satellite images to map coseismic surface deformation along the northern segment of the BBE, a few hundred meters east of the urban area of Bam. Using a new approach based on principal component analysis (PCA) on offset measurements, we obtain 1.8 ± 0.6 cm east slip component and 2–6 ± 0.6 cm south slip component along the fault segment. Our results are consistent with ground observations over the study area and support the idea of the reactivation of the shallow part of this fault segment.

A.5 Cruz-Atienza, V., J. Virieux and H. Aochi (2007)

Numerical simulations on faulting : Microscopic evolution, macroscopic interaction and rupture process of earthquakes

Geophysics, 72, SM123–SM137

Proper understanding of seismic emissions associated with the growth of complexly shaped microearthquake networks and larger-scale nonplanar fault ruptures, both in arbitrarily heterogeneous media, requires accurate modeling of the underlying dynamic processes.We present a new 3D dynamic-rupture, finitedifference model called the finite-difference, fault-element (FDFE) method ; it simulates the dynamic rupture of nonplanar faults subjected to regional loads in complex media. FDFE is based on a 3D methodology for applying dynamic-rupture boundary conditions along the fault surface. The fault is discretized by a set of parallelepiped fault elements in which specific boundary conditions are applied. These conditions are applied to the stress tensor, once transformed into a local fault reference frame. Numerically determined weight functions multiplying particle velocities around each element allow accurate estimates of fault kinematic parameters (i.e., slip and slip rate) independent of faulting mechanism. Assuming a Coulomb-like slip-weakening friction law, a parametric study suggests that the FDFE method converges toward a unique solution, provided that the cohesive zone behind the rupture front is well resolved (i.e., four or more elements inside this zone). Solutions are free of relevant numerical artifacts for grid sizes smaller than approximately 70 m. Results yielded by the FDFE approach are in good quantitative

agreement with those obtained by a semianalytical boundary integral method along planar and nonplanar parabola-shaped faults. The FDFE method thus provides quantitative, accurate results for spontaneous-rupture simulations on intricate fault geometries.

A.6 Douglas, J., H. Aochi, P. Suhadolc and G. Costa (2007)

The importance of crustal structure in explaining the observed uncertainties in ground motion estimation

Bull. Earthquake Eng., 5, 17–26

In this short article, the possible reduction in the standard deviation of empirical ground motion estimation equations through the modelling of the effect of crustal structure is assessed through the use of ground-motion simulations. Simulations are computed for different source-to-site distances, focal depths, focal mechanisms and for crustalmodels of the Pyrenees, the western Alps and the upperRhine Graben. Through the method of equivalent hypocentral distance introduced by Douglas et al. [(2004) Bull Earthquake Eng 2(1) : 75–99] to model the effect of crustal structure in empirical equations, the scatter associated with such equations derived using these simulated data could be reduced to zero if real-to-equivalent hypocentral distance mapping functions were derived for every combination of mechanism, depth and crustal structure present in the simulated dataset. This is, obviously, impractical. The relative importance of each parameter in affecting the decay of ground motions is assessed here. It is found that variation in focal depth is generally more important than the effect of crustal structure when deriving the real-to-equivalent hypocentral distance mapping functions. In addition, mechanism and magnitude do not have an important impact on the decay rate.

A.7 Aochi, H. and J. Douglas (2006)

Testing the Validity of Simulated Strong Ground Motion from the Dynamic Rupture of a Finite Fault, by Using Empirical Equations

Bull. Earthquake Eng., 4, 211–229

This paper is concerned with testing the validity of the ground motions estimated by combining a boundary integral equation method to simulate dynamic rupture along finite faults with a finite difference method to compute the subsequent wave propagation. The validation exercise is conducted by comparing the calculated ground motions at about 100 hypothetical stations surrounding the pure strike-slip and pure reverse faults with those estimated by recent ground motion estimation equations derived by regression analysis of observed strong-motion data. The validity of the ground motions with respect to their amplitude, frequency content and duration is examined. It is found that the numerical simulation method adopted leads to ground motions that are mainly compatible with the magnitude and distance dependence modelled by empirical equations but that the choice of a low stress drop leads to ground motions that are smaller than generally observed. In addition, the scatter in the simulated ground motions, for which a laterally homogeneous crust and standard rock site were used, is of the same order as the scatter in observed motions therefore, close to the fault, variations in source propagation likely contribute a significant proportion of the scatter in observed motions in comparison with travel-path and site effects.

A.8 Aochi, H. O. Scotti and C. Berge-Thierry (2005)

Dynamic transfer of rupture across differently oriented segments in a complex 3-D fault system

Grophys. Res. Lett., 32, L21304, doi :10.1029/2005GL024158

We simulate spontaneous dynamic propagation of rupture across two adjacent fault segments, subject to a triaxial compressive stress regime. These segments have different orientations and hence different focal mechanisms (vertical strike-slip and dipping thrust). Numerical simulations, using a BIEM (boundary integral equation method), have revealed that, under a typical triaxial homogeneous compressive stress regime where the magnitude of the intermediate principal stress lies halfway between those of the maximum and minimum ones, ruptures of different focal mechanisms are not likely to occur simultaneously in a single rupture event. Propagation of rupture from a vertical strike-slip fault segment to a pure dip-slip (normal/reverse) fault segment is possible only when the stress field is close to uniaxial compression, or when the intermediate stress magnitude is close either to the minimum or the maximum one. These findings are useful for evaluating possible earthquake scenarios along fault systems with complex 3D geometries.

A.9 Aochi, H. and K. B. Olsen (2004)

On the Effects of Non-planar Geometry for Blind Thrust Faults on Strong Ground Motion

Pure Appl. Geophys., 161, 2139–2153

We quantify the effects of complex fault geometry on low-frequency (¡ 1 Hz) strong ground motion using numerical modeling of dynamic rupture. Our tests include the computation of synthetic seismograms for several simple rupture scenarios with planar and curved fault approximations of the 1994 Northridge earthquake. We use the boundary integral equation method (BIEM) to compute the dynamic rupture process, which includes the normal stress effects along the curved fault geometries. The wave propagation and computation of synthetic seismograms are modeled using a fourth-order finitedifference method (FDM). The near-field ground motion is significantly affected by the acceleration, deceleration and arrest of rupture due to the curvature of the faults, as well as the variation in directivity of the rupture. For example, a 6-km-long hanging-wall or footwall splay with a maximum offset of 1 km can change 1-Hz peak velocities by up to a factor of 2-3 near the fault. Our tests suggest that the differences in waveform are larger on the hanging wall compared to those on the footwall, although the differences in amplitude are larger in the forward rupture direction (footwall). The results imply that kinematic ground motion estimates may be biased by the omission of dynamic rupture effects and even relatively gentle variation in fault geometry, and even for long-period waves.

A.10 Aochi, H. and S. Ide (2004)

Numerical study on multi-scaling earthquake rupture

Geophys. Res. Lett., 31, L02606, doi :10.1029/2003GL018708

A new numerical scheme using a renormalization and a 3D boundary integral equation method is proposed to simulate a multi-scaling dynamic rupture of earthquakes : How a small earthquake grows up to a large one in spatially heterogeneous field of critical slip-weakening distance Dc (fracture energy Gc) ? We examine the case where Dc grows according to a hypocentral distance L (Dc $\propto$ L$^{\beta}$). When $\beta = 1$, we succeed to show numerically that a rupture propagates at a constant rupture speed in uniform initial stress field. This result still keeps the scaling relation of Gc and Dc inferred for earthquake size, however no scale-dependent initial process is required. The break of the proportional relation changes rupture speed as well as slip velocity to keep the energy balance. The rupture is accelerated up to a speed even faster than the shear wave velocity (β ¡ 1) or naturally arrested (β ¿ 1).

A.11 Aochi, H. and R. Madariaga (2003)

The 1999 Izmit, Turkey, Earthquake : Nonplanar Fault Structure, Dynamic Rupture Process, and Strong Ground Motion

Bull. Seism. Soc. Am., 93, 1249–1266

We simulated dynamic rupture propagation along various nonplanar fault models of the 1999 I ?zmit, Turkey, earthquake using a boundary integral equation method. These models were inferred from geological and geodetic observations. Based on these results, we modeled seismic-wave propagation around the fault system using a finite difference method. We focused on the effect of different fault geometries on the rupture process and seismic-wave propagation. Numerical simulation results imply a rapid and continuous rupture propagation from the Izmit– Sapanca Lake segment to the Sapanca–Akyazi segment. The rupture under Sapanca Lake appears to have propagated not on a disconnected fault segment but along a smooth fault structure with a bend of only a few degrees. The observational complexity of the surface breaks, however, can be best simulated by a highly segmented fault model. This infers that fault geometric characters observed in the field reflect near-surface structure and that seismological and geodetic features are controlled by global fault structure at depth.

Then we investigated the effect of frictional parameters and the initial stress field. In order to explain near-field seismograms at station SKR, located a distance of a few kilometers from the fault, we had to force the rupture to propagate at shallow depth close to the station. In order to obtain this, we had to introduce a finite cohesive force in the friction law that allows stress accumulation and release in the shallow crust. The external stress field had to be large enough for the rupture to propagate at very rapid speed. Our simulation results show that it is important to include detailed fault geometry in the numerical simulation, and to constrain frictional parameters and the initial stress field, for understanding of the full dynamic process of an earthquake.

A.12 Aochi, H., E. Fukuyama, and R. Madariaga (2003)

Constraint of fault parameters inferred from nonplanar fault modeling

Geochemistry, Geophysics, Geosystems, 4, doi :10.1029/2001GC000207

We study the distribution of initial stress and frictional parameters for the 28 June 1992 Landers, California, earthquake through dynamic rupture simulation along a nonplanar fault system. We find that observational evidence of large slip distribution near the ground surface requires large nonzero cohesive forces in the depth-dependent friction law. This is the only way that stress can accumulate and be released at shallow depths. We then study the variation of frictional parameters along the strike of the fault. For this purpose we mapped into our segmented fault model the initial stress heterogeneity inverted by Peyrat et al. [2001] using a planar fault model. Simulations with this initial stress field improved the overall fit of the rupture process to that inferred from kinematic inversions, and also improved the fit to the ground motion observed in Southern California. In order to obtain this fit, we had to introduce an additional variations of frictional parameters along the fault. The most important is a weak Kickapoo fault and a strong Johnson Valley fault.

A.13 Aochi, H., R. Madariaga, and E. Fukuyama (2002)

Effect of normal stress during rupture propagation along nonplanar faults

J. Geophys. Res., 107, 10.1029/2001JB000500

We study a symmetrical three-forked shear fault under simple triaxial stress. Rupture initiates in the central primary plane and propagates toward the branching point. One of the two branches is in the compressional quadrant, while the other is in the tensional domain. We study the following question : Does rupture always prefer propagating along the tensional branch because of the effect of normal stress ? When the primary plane is located in the most favorable direction as determined by Mohr-Coulomb criterion, one finds that the compressional branch is almost always preferred for various dynamic coefficients and confining pressures. Simultaneous rupture propagation on both branches appears only under a very special condition found by Aochi et al. [2000b]. These results indicate that shear stress changes produced by the rupture front dominate during dynamic rupture propagation, compared to normal stress changes. This result depends completely on the orientation of the whole fault system. In all cases, we can explain the branch selection by analyzing the applied initial shear stress and the fault properties. Change of normal stress may play a role similar to shear stress change for disjoint faults since the effect of normal stress change sometimes dominates.

A.14 Aochi, H. and M. Matsu'ura (2002)

Slip- and Time-dependent Fault Constitutive Law and its Significance in Earthquake Generation Cycles

Pure Appl. Geophys., 159, 2029–2044

By integrating effects of microscopic interactions between statistically self-similar fault surfaces, we succeeded in deriving a slip- and time-dependent fault constitutive law that rationally unifies the slip-dependent law and the rate- and state-dependent law. In this constitutive law the slip-weakening results from the abrasion of surface asperities that proceeds irreversibly with fault slip. On the other hand, the restoration of shear strength after the arrest of faulting results from the adhesion of surface asperities that proceeds with contact time. At the limit of high slip-rate the unified constitutive law is reduced to the slip-weakening law. At the limit of low slip-rate it shows the well-known log t strengthening of faults over the wide range of contact time t. In the steady state with a constant slip-rate V the shear strength has the negative log V dependence, known as the velocity-weakening. Another important property expected from the unified constitutive law is the gradual increase of the critical weakening displacement Dc with stationary contact time. We numerically examined behavior of a single degree of freedom elastic system following the slip- and time-dependent constitutive law, and found that the periodic stick-slip motion is realized when the adhesion rate is high in comparison with the loading rate. If the adhesion rate is very low, behavior of the system gradually changes from stick-slip motion to steady sliding with time.

A.15 Aochi, H., E. Fukuyama and M. Matsu'ura (2000b)

Selectivity of spontaneous rupture propagation on a branched fault

Geophys. Res. Lett., 27, 3635–3638

We simulated spontaneous dynamic rupture propagation on a branched fault system using the boundary integral equation method (BIEM) in 3D homogeneous, unbounded elastic medium. From the numerical experiments, we found that slightly heterogeneous preload stress field on the

branches caused selective rupture propagation. Dynamic rupture propagation spontaneously on both branches requires very delicate conditions for the initial stress field as well as for the fracture criterion on them.

A.16 Aochi, H., E. Fukuyama and M. Matsu'ura (2000a)

Spontaneous Rupture Propagation on a Non-planar Fault in 3-D Elastic Medium

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Abstract—We constructed a new calculation scheme of spontaneous rupture propagation on non-planar faults in a 3-D elastic medium using a boundary integral equation method (BIEM) in time domain. We removed all singularities in boundary integral equations (BIEs) following the method proposed by FUKUYAMA and MADARIAGA (1995, 1998) for a planar fault in a 3-D elastic medium, and analytically evaluated all BIEs for a basic box-like discrete source. As an application of the new calculation scheme, we simulated rupture propagation on a bending fault subjected to uniform triaxial compression and examined the effect of fault bend upon the dynamic rupture propagation. From the numerical results, we found that rupture propagation is decelerated or arrested for some combination of inclined angle of the bending fault and absolute value of the fault strength. The most significant effect of bending is the nonuniform distribution of pre-loaded shear stress due to different orientation of the fault plane under a uniform tectonic stress regime. Our results also indicate that low absolute shear stress level is required to progress the rupture propagation ahead of the inclined fault.

B Extrait of Papers

B.1 Aochi, H., M. Cushing, O. Scotti, C. Berge-Thierry (2006)

B.2 Ide, S. and H. Aochi (2005)

B.3 Aochi, H. and E. Fukuyama (2002)