Natural Disaster Science and Mitigation Engineering:
DPRI Reports

Hiroshi Kawase *Editor*

Studies on the 2011 Off the Pacific Coast of Tohoku Earthquake

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Hiroshi Kawase
Editor

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Editor
Hiroshi Kawase
Disaster Prevention Research Institute (DPRI)
Kyoto University
Kyoto, Japan

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Foreword

On the afternoon of March 11, 2011, a huge earthquake and accompanying tsunamis caused horrifying damage in the northern part of Japan, taking the lives of more than 18,900 people in the Tohoku region. This event evolved into the most widespread and complicated disaster in the modern history of disasters in Japan. On behalf of the Disaster Prevention Research Institute (DPRI) of Kyoto University, I hereby express my sincere condolences for those who lost their families and friends, to those who lost their homes and workplaces, and to those who were forced to leave their hometowns.

DPRI was founded in 1951 in response to serious damage caused by a huge typhoon that struck Japan in that year. DPRI researches nearly all natural hazards, including earthquakes and volcanic explosions, floods, tsunamis, tidal waves, typhoons and other atmospheric phenomena, and landslides and associated geohazards. The researchers who work in DPRI have specialties extending from natural science, engineering, and informatics, to social sciences. With such coverage, we conduct comprehensive research ranging from the prediction of hazards and investigation into their mechanisms, development of technologies to prevent and reduce associated disasters, analysis and measures of response and recovery immediately after disasters, to methodologies for disaster risk management. DPRI also serves as a national research center in which researchers working for Japanese universities on natural disasters and their prevention and/or mitigation use the experimental and observatory facilities owned by DPRI and work jointly with the DPRI researchers.

The six decades since the inception of DPRI have been marked by a notable increase in the degree and intensity of natural disasters. Various factors, both natural and social, are responsible for the changes. The severity of extreme weather phenomena (such as flood and drought) has escalated due primarily to recent climate variations. Rapid urbanization and densification also have contributed to the increased impact of disasters. The 1995 Hanshin-Awaji Disaster killed more than 6,000 people. The disaster was caused by an inland fault rupture, and numerous houses and buildings located in the city of Kobe and its neighboring towns collapsed because of very intense near-fault ground motions. In the 2011 Tohoku Disaster, the huge tsunamis caused by an ocean-ridge earthquake of magnitude 9.0 were the primary cause of the death toll. This most recent disaster was also characterized by the vastness of the affected regions and by the complexity in which one disaster triggered another, as the overall catastrophe evolved into a perfect storm of disaster. The unprecedented risks disclosed by this calamity pose many challenges for us to overcome.

In response to the numerous lessons learned from this disaster, DPRI has initiated a comprehensive research effort on the establishment of a more resilient society, in which both safety and security are ensured against huge natural disasters such as the 2011 Tohoku Disaster. Along the lines of this effort, DPRI hereby wants to offer a series of volumes titled Natural Disaster Science and Mitigation Engineering, published by Springer, with the intention of sharing with international communities that have been engaged in natural disasters and mitigation our experiences and knowledge accumulated in these decades. The volumes include the surveys and findings acquired from a number of research projects led by DPRI researchers, post-disaster investigations into the causes and effects of the disaster, and a series of recommendations for the advancement of various measures to prevent and/or reduce disasters that could hit our globe in the coming years.

Masayoshi Nakashima
Director
Disaster Prevention Research Institute (DPRI)
Kyoto University

Preface

This is the first volume of the Disaster Prevention Research Institute (DPRI) series of reports titled Natural Disaster Science and Mitigation Engineering, published by Springer Japan. This volume is devoted to the surveys and findings from a number of projects led by DPRI researchers on the earthquake that occurred off the Pacific Coast of Tohoku on March 11, 2011, and the subsequent disaster, referred to here as the Great East Japan Disaster. The earthquake is considered to have caused complex, widespread, and long-lasting disaster sequences all over Japan as well as in other parts of the world.

The impact of the earthquake and disaster can be seen in almost all aspects of social activities in Japan. It is totally beyond my expertise to summarize its impact; however, I would like to note here one major issue raised in the seismic and earthquake engineering community as a direct consequence of the disaster and one major issue that has not been raised yet but should be.

Before the earthquake, the national Headquarters for Earthquake Research Promotion (HERP) provided National Seismic Hazard Maps for Japan to the public. On those maps, all the major sources of the probabilistic occurrence of earthquakes supposedly had been evaluated quantitatively, reflecting all of the current best knowledge of seismology, geology, geomorphology and tectonics. Despite about eight years of serious efforts, the HERP failed to predict the occurrence of the Tohoku disaster. Precisely speaking, they failed to include a scenario with such a large magnitude as that of the earthquake off the Tohoku coast.

There are many reasons for not including that possible scenario in their calculation of the seismic hazard in Tohoku, and technically it is relatively easy to fix the problem after the occurrence (actually, the basic hazard level of ground motions would not be much different even if we consider that scenario because of its low recurrence rate). However, the fundamental issue raised is not just models to be used but the credibility of the hazard map itself, which is quite a political and/or sociological issue. If we think that it is a safe bet for predictors to raise the probability in response to such an extraordinary scenario, we can always include an extreme case, such as one scenario beyond the rational expectation based on previous data. The M9 scenario of the Central Disaster Management Council, Cabinet Office, Government of Japan seems a good example of that kind of extreme scenario, to which we cannot assign any rational value of probability because it has never happened before in the long history of earthquake occurrence along the Nankai Trough subduction zone. We can call this kind of psychological/political tendency of public skepticism regarding hazard estimates "A burnt child dreads the fire" syndrome. This is not a scientific issue but rather a sociological one regarding the experts' responsibility to the public on the subject of hazard estimates. I believe that a rational person would prefer to be told the actual truth rather than exaggerations even when there was the good motivation of preventing unexpected disaster.

Another issue that has not been raised yet but should be brought up is the adequacy of the current seismic code in Japan. Despite the high peak accelerations widely observed in the eastern part of Tohoku as well as in the northern part of the Kanto region, structural damages to buildings were minimal, probably less than 10% of the total structural damage, and probably fewer than 100 people were killed as a direct consequence of building collapses, including falling furniture and debris, together with objects falling due to other, non-structural damage. We can call it a victory of Japanese seismic design and practice. However, if no damage from any earthquakes is what we require, we just need to make buildings safer no matter what the ground motions at a site will be. Apparently the 2011 earthquake shows that buildings are actually much stronger than required by the seismic design code so that there is a large gap between the reality and the theory. If no structural experts considered any modification of the current seismic code and no building owners in Japan complained because of the "unexpectedly good" performance of the current (probably expensive) buildings, the reality–theory gap means nothing to anyone. However, as soon as we consider a modification of the code in one way or another, we must face the mystery of our stock of buildings for their "unexpectedly good" performance.

As readers will see, this volume is not intended to resolve these specific issues, but several chapters may have a stronger relation to these issues than others have. I hope that readers will find the content of this volume interesting and will use the information herein to consider these issues and other issues that the Tohoku earthquake and the subsequent disaster raised, both in Japan and in the rest of the world, in order to build a safer and more secure society.

Hiroshi Kawase
Editor
Disaster Prevention Research Institute (DPRI)
Kyoto University

Contents

Contributors

Shin Aoi National Research Institute for Earth Science and Disaster Prevention (NIED), Tsukuba, Japan (Chapter 3)

Kimiyuki Asano Disaster Prevention Research Institute (DPRI), Kyoto University, Kyoto, Japan (Chapter 3)

Ryokei Azuma Disaster Prevention Research Institute (DPRI) of Kyoto University, Kyoto, Japan (Chapter 4)

Yasuyuki Baba Disaster Prevention Research Institute (DPRI) of Kyoto University, Kyoto, Japan (Chapter 4)

Yasunori Ban Disaster Prevention Research Institute (DPRI), Kyoto University, Kyoto, Japan (Chapter 8)

Masahiro Chigira Disaster Prevention Research Institute (DPRI), Kyoto University, Kyoto, Japan (Chapters 6, 11)

Takeshi Enomoto Disaster Prevention Research Institute (DPRI), Kyoto University, Kyoto, Japan (Chapter 13)

Yoshinori Fujino NEWJEC Inc., Osaka, Japan (Chapter 7)

Shinya Fujiwara Kokusai Kogyo Co. Ltd., Tokyo, Japan (Chapter 6)

Yui Fukuda NEWJEC Inc., Osaka, Japan (Chapter 7)

Yo Fukushima Disaster Prevention Research Institute (DPRI), Kyoto University, Kyoto, Japan (Chapter 2)

Koji Hada NEWJEC Inc., Osaka, Japan (Chapter 7)

Manabu Hashimoto Disaster Prevention Research Institute (DPRI), Kyoto University, Kyoto, Japan (Chapter 2)

Takashi Hayakawa Institute of Technology, Shimizu Corporation, Tokyo, Japan (Chapter 9)

Takao Iguchi Disaster Prevention Research Institute (DPRI), Kyoto University, Kyoto, Japan (Chapter 13)

Hirohiko Ishikawa Disaster Prevention Research Institute (DPRI), Kyoto University, Kyoto, Japan (Chapter 12)

Tomotaka Iwata Disaster Prevention Research Institute (DPRI), Kyoto University, Kyoto, Japan (Chapter 3)

Toshitaka Kamai Disaster Prevention Research Institute (DPRI) of Kyoto University, Kyoto, Japan (Chapter 8)

Hiroshi Kawase Disaster Prevention Research Institute (DPRI), Kyoto University, Kyoto, Japan (Chapters 1, 9)

Takashi Kunugi National Research Institute for Earth Science and Disaster Prevention (NIED), Tsukuba, Japan (Chapter 3)

Shinichi Matsushima Disaster Prevention Research Institute (DPRI), Kyoto University, Kyoto, Japan (Chapter 9)

Yuki Matsushi Disaster Prevention Research Institute (DPRI), Kyoto University, Kyoto, Japan (Chapter 11)

Sumio Matsuura Disaster Prevention Research Institute (DPRI), Kyoto University, Kyoto, Japan (Chapter 11)

Hitoshi Mukougawa Disaster Prevention Research Institute (DPRI), Kyoto University, Kyoto, Japan (Chapter 13)

Hidehiko Murao Murao Chiken Co., Ltd., Toyama, Japan (Chapter 8)

Fumiaki Nagashima Disaster Prevention Research Institute (DPRI), Kyoto University, Kyoto, Japan (Chapter 9)

Akito Nakasuji Kokusai Kogyo Co. Ltd., Tokyo, Japan (Chapter 6)

Hidemasa Ohta Ohta Geo-Research Co., Ltd., Nishinomiya, Japan (Chapter 8)

Takashi Okamoto Forestry and Forest Products Research Institute (FFPRI), Tsukuba, Japan (Chapter 11)

Mitsutaka Oshima Institute of Technology, Shimizu Corporation, Tokyo, Japan (Chapter 9)

Masayuki Sakagami Kokusai Kogyo Co. Ltd., Tokyo, Japan (Chapter 6)

Francisco J. Sánchez-Sesma Institute of Engineering, UNAM, Mexico City, Mexico (Chapter 9)

Toshimi Satoh Institute of Technology, Shimizu Corporation, Tokyo, Japan (Chapter 9)

Haruko Sekiguchi Disaster Prevention Research Institute (DPRI), Kyoto University, Kyoto, Japan (Chapter 3)

Christine Smyth Disaster Prevention Research Institute (DPRI), Kyoto University, Kyoto, Japan (Chapter 7)

Wataru Suzuki National Research Institute for Earth Science and Disaster Prevention (NIED), Tsukuba, Japan (Chapter 3)

Youichiro Takada Disaster Prevention Research Institute (DPRI), Kyoto University, Kyoto, Japan (Chapter 2)

Tetsuya Takemi Disaster Prevention Research Institute (DPRI), Kyoto University, Kyoto, Japan (Chapter 12)

Shuji Tamura Disaster Prevention Research Institute (DPRI), Kyoto University, Kyoto, Japan (Chapter 10)

Tetsuya Hiraishi Disaster Prevention Research Institute (DPRI), Kyoto University, Kyoto, Japan (Chapter 4)

Masumi Yamada Disaster Prevention Research Institute (DPRI), Kyoto University, Kyoto, Japan (Chapter 7)

Masayuki Yamada NEWJEC Inc., Osaka, Japan (Chapter 7)

Katsuya Yamori Disaster Prevention Research Institute (DPRI), Kyoto University, Kyoto, Japan (Chapter 5)

Nozomi Yoneyama Disaster Prevention Research Institute (DPRI), of Kyoto University, Kyoto, Japan (Chapter 4)

Chapter 1
Introduction

Hiroshi Kawase

Abstract The Tohoku earthquake on March 11, 2011, officially named as "Off the Pacific Coast of Tohoku, Japan Earthquake" by JMA, caused an unprecedentedly severe disaster on the northeastern part of Honshu (Tohoku), Japan. In this first volume of the series of books, namely, Natural Disaster Science and Mitigation Engineering: DPRI reports, we covered various aspects of investigations on scientific findings as well as issues related to the disaster and the subsequent evacuation due to the earthquake. The series of books presents recent advances in natural disaster sciences and mitigation technologies developed in Japan, which would be valuable for the mitigation of disasters due to similar kind of future events around the world.

The Mw9.0 Tohoku, Japan, earthquake on March 11, 2011, which is officially named as the 2011 Off the Pacific Coast of Tohoku, Japan Earthquake by Japan Meteorological Agency (JMA), could be the largest event in Japanese history. The earthquake is the so-called mega-thrust event at the plate interface between the North American Plate and the Pacific Plate, which generated a huge tsunami that devastated towns on the coast and brought over 18,000 fatalities and missing. About 100,000 houses were totally lost mainly due to tsunamis, and the total estimated direct loss would be over 200 billion US dollars. The level VI accident at the Fukushima Daiichi nuclear power plant of Tokyo Electric Power Co. was also due to the unexpected level of the tsunami height at the plant.

It is essential to investigate various aspects of the disaster in order to prevent this kind of tragic event happen again. To that end DPRI initiated emergency investigation collaboration projects to perform the field surveys and data analyses in close collaboration with other researchers at different universities and institutions

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H. Kawase (✉)
Disaster Prevention Research Institute (DPRI), Kyoto University, Kyoto, Japan
e-mail: kawase@zeisei.dpri.kyoto-u.ac.jp

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immediately after the earthquake. This volume includes findings acquired from a number of reconnaissance teams lead by DPRI researchers and post-earthquake investigations into the causes and effects of the disaster.

In Chaps. 2 and 3, we collect reports on the source characterization of the main shock based on the geophysical data in the two extreme period ranges, one for infinitely long period and the other for short period up to several tens of seconds.

In Chaps. 4 and 5, we report the field survey results of the tsunami damage in the Tohoku district and the problems associated with the evacuation process from tsunami in the Tohoku district. We also collect the reports for the induced soil slide observed widely in the Tohoku district in Chap. 6 as natural phenomenon caused by the earthquake. Then from Chaps. 7 to 9, we collect investigation focused on man-made structures such as buildings and man-made slopes.

In Chaps. 10 and 11 we collect reports on the damage on ground due to liquefaction and landslide with the heavy snow coverage. Finally, we have two chapters, Chaps. 12 and 13, on meteorological surveys to trace the diffusion process of radioactive release by the Fukushima NPP accident.

As you can notice, we have collected variety of investigation reports on various aspects of the Tohoku disaster, which may provide invaluable information to initiate further detailed studies to prevent/mitigate similar disasters in future anywhere in the world.

Chapter 2
Coseismic Deformations of the 2011 Tohoku, Japan, Earthquake and Triggered Events Derived from ALOS/PALSAR

Manabu Hashimoto, Yo Fukushima, and Youichiro Takada

Abstract The Tohoku earthquake on March 11, 2011, caused a remarkably large deformation on the island of Honshu, Japan. By analyzing ALOS/PALSAR data, a range increase of up to 3.6 m at the tip of the Oshika Peninsula, the closest point to the epicenter, was detected from ascending orbits. Combining ascending and descending interferograms, this peninsula was confirmed to have subsided and shifted eastward. This deformation may have been caused by a huge reverse slip on the plate interface near the trench axis.

This large deformation induced local earthquakes with magnitudes of 6 or larger and volcanic unrests. Among them, the April 11 M7.0 event in southern Fukushima Prefecture occurred on previously unrecognized active faults. More than nine fringes showing range increases were found in the vicinity of the epicenter of the Fukushima event. This observation is consistent with normal faulting on faults whose motion was previously not recognized. We also found slight range increases in volcanic regions in Northeast Japan. These observations imply that the March 11 shock induced large extensional stress in the crust of eastern Japan.

Keywords ALOS/PALSAR • Crustal deformation • Synthetic aperture radar • Triggered events

2.1 Introduction

The Mw9.0 Tohoku, Japan, earthquake on March 11, 2011, is the largest event in Japanese history. The Global CMT solution implies large thrust faulting on the plate interface (Fig. 2.1), which generated a huge tsunami that devastated towns on the coast and brought 18,812 fatalities and missing as of June 20, 2012.

M. Hashimoto (✉) • Y. Fukushima • Y. Takada
Disaster Prevention Research Institute (DPRI), Kyoto University, Kyoto, Japan
e-mail: hashimoto.manabu.7e@kyoto-u.ac.jp

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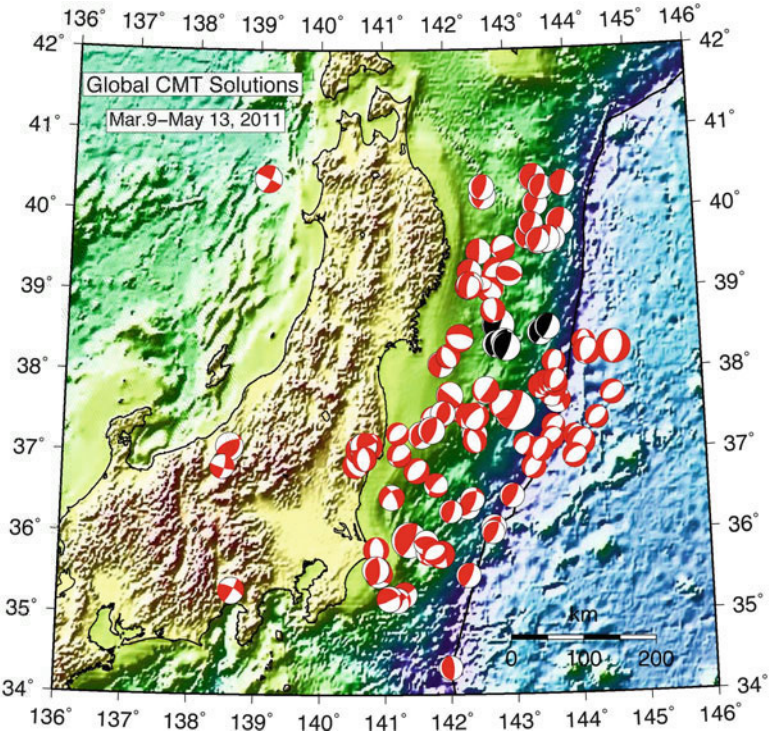

Fig. 2.1 Distribution of CMT solutions of events (Mw > 6.0) during March 9 to May 13, 2011 (Harvard University Global CMT 2011). *Black symbols* are those for foreshocks. The biggest one is for the mainshock

It is essential to reveal deformations on the Japanese islands in order to understand the mechanism of this extreme event and to improve long-term forecasting. A dense continuous GPS observation network (GSI's Earth Observation Network; GEONET) has been deployed by the Geospatial Information Authority, Japan (e.g., Sagiya 2004), and the coseismic deformation was immediately reported based on its data (Ozawa et al. 2011; Simons et al. 2011). Synthetic Aperture Radar Interferometry (InSAR) is another suitable technique for the detection of crustal deformation. InSAR has an advantage in its spatial resolution over GPS. After the main shock of the Tohoku earthquake a lot of earthquakes and volcanic unrest were induced all over eastern Japan. InSAR is the best method to detect coseismic deformation associated with these induced events, because the size of these events is comparable to or smaller than the spacing of the network of GEONET.

Since its launch in 2006, the Advanced Land Observation Satellite (ALOS) has been making observations of the Earth. ALOS has a SAR sensor, the Phased Array-type L-band SAR (PALSAR). PALSAR gives us excellent data which reveal coseismic deformations such as the 2008 Wenchuan and the 2010 Haiti earthquakes (e.g., Hashimoto et al. 2010; Hashimoto et al. 2011). We have been working for the

Earthquake Working Group, a special project for the Evaluation of ALOS for the Disaster Mitigation, under the coordination of GSI and the Japan Aerospace Exploration Agency (JAXA), since 2007. When a large earthquake occurs, the working group requests urgent observations and analyses acquired images. Unfortunately, ALOS terminated its operation due to a sudden power failure on April 22. It is regrettable that the PALSAR images of the Tohoku earthquake are the last message from ALOS. In this report, we show results of analyses of PALSAR images acquired before and after the 2011 Tohoku earthquake.

2.2 Acquisition of ALOS/PALSAR

PALSAR has two modes of observation useful for InSAR: strip-map and ScanSAR mode. Strip-map mode images are ~70 km wide and have a high spatial resolution. On the other hand, ScanSAR mode images are ~350 km wide, but the spatial resolution is low. Furthermore a synchronization of bursts between two ScanSAR images is required to obtain high coherence. Therefore we requested JAXA to acquire both modes of images depending on the conditions such as the availability of archived images or conflict with other observations.

Unfortunately, ALOS experienced a power failure on April 22, and JAXA announced the completion of operation in May. Therefore we could not obtain full coverage of eastern Japan, but the ALOS/PALSAR data gave us invaluable information on the biggest earthquake in the history of Japan.

2.3 Image Processing

Strip-map mode images are acquired from ascending orbits, while ScanSAR mode images are obtained from descending orbits. Two strip-map mode pairs are also acquired from descending orbits. Precise orbits are used in processing. Unfortunately the perpendicular baselines for the ScanSAR–ScanSAR pairs are longer than 2,000 m, which resulted in only partially coherent interferograms. Therefore, we only show strip-map interferograms here.

We processed images with Gamma®. A hole-filed SRTM digital elevation model (Jarvis et al. 2008) was used for the 2-pass differential interferometry.

2.4 The March 11 Mainshock

First, we discuss the deformation field observed by PALSAR. Figures 2.2 and 2.3 show the ascending and descending interferograms, respectively. We obtained high coherence in the plain area, but coherence is relatively low in the mountains. This low coherence may be attributed mainly to snow coverage.

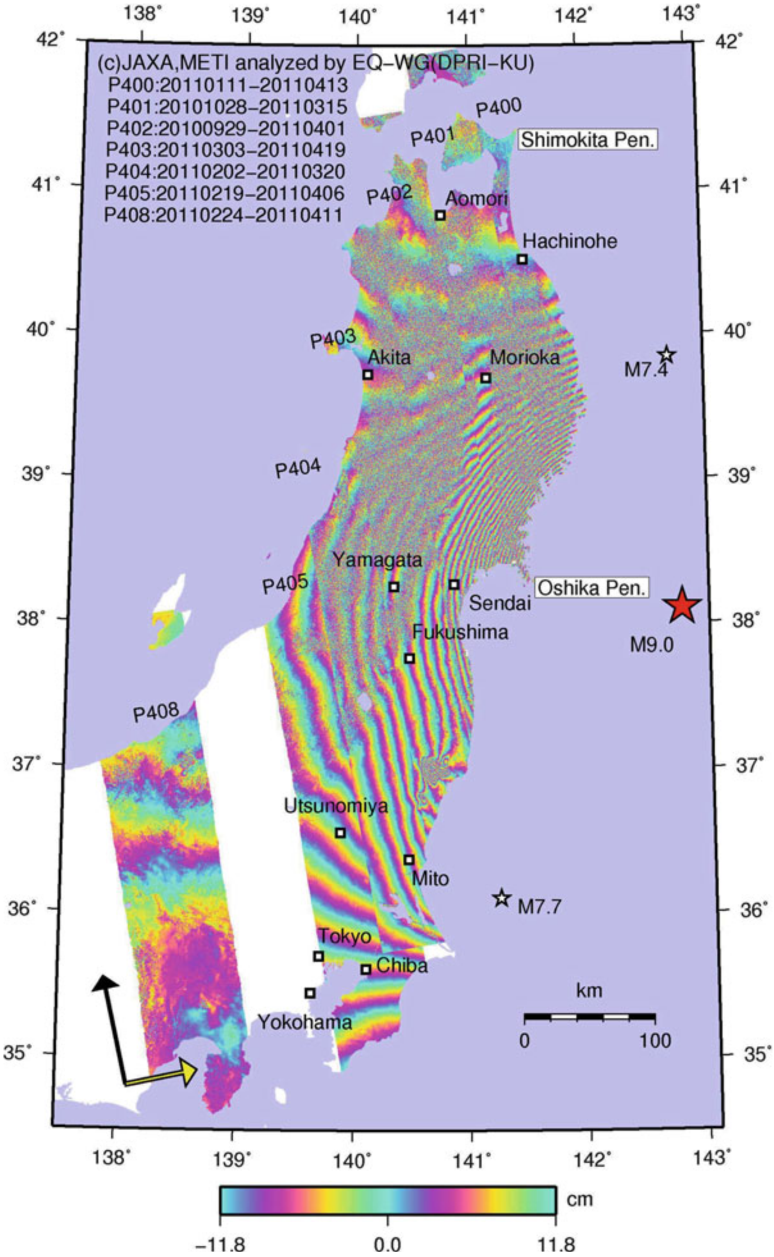

Fig. 2.2 Asecnding interferograms. 1 cycle of color scale indicates 11.8 cm changes in line of sight distance. Black and yellow arrows show the direction of flight of satellite and line of sight, respectively. Red and white stars denotes the epicenter of the mainshock and aftershocks, respectively

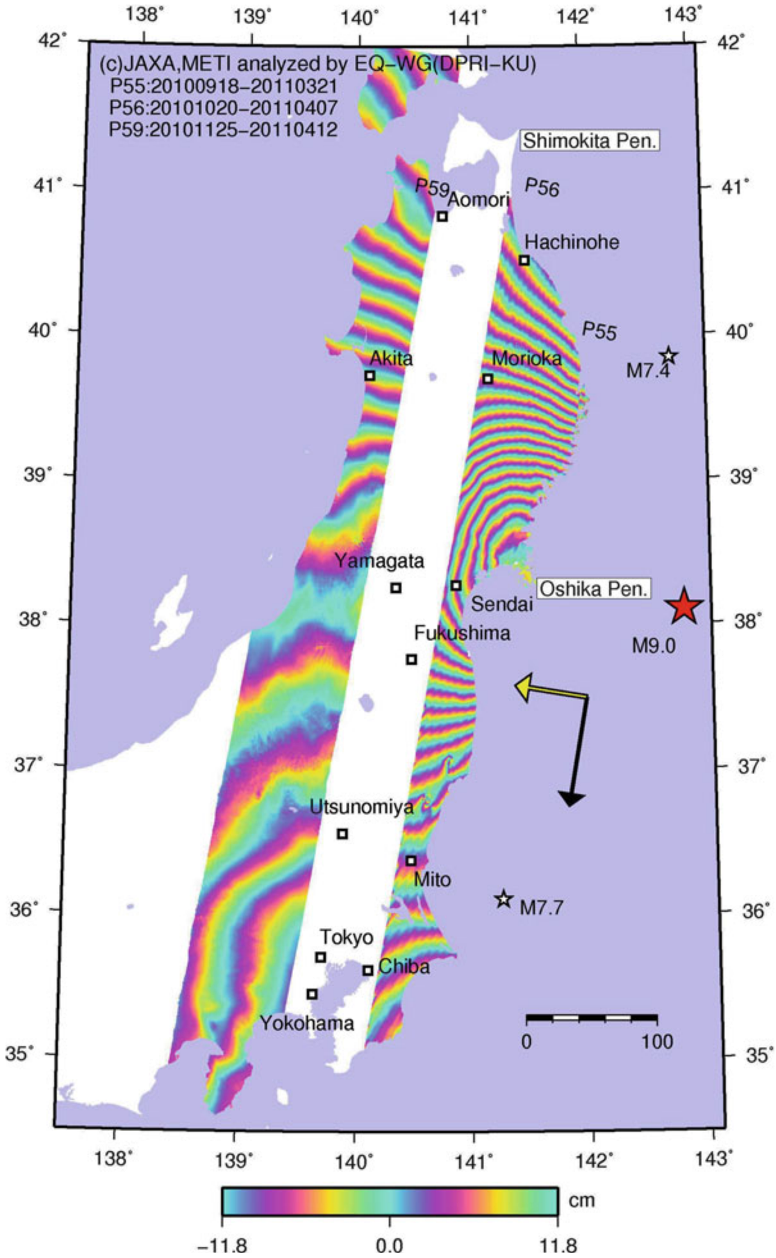

Fig. 2.3 Desecending interferograms. See also Legend of the Fig. 2.2.