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Conclusions

PRADEEP TALWANI

This book presents the results of studies of intraplate earthquakes in eight diverse regions of the world (Chapters 2 to 9). Together they present an opportunity to confirm or modify our current ideas and to devise future studies aimed at improving our understanding of this phenomenon. These chapters primarily address the spatial and temporal pattern of intraplate earthquakes and, where possible, identify the seismic sources. In some cases the authors speculate on the mechanisms responsible for the seismicity. Chapter 10 confirms our understanding on how stresses originating at plate boundaries are responsible for mid-plate earthquakes. The unified model for intraplate earthquakes (Chapter 11) presents a synthesis of earlier models into a testable one, while Chapter 12 on seismic hazards cautions against the continued use of probabilistic seismic hazard analysis methodology for intraplate earthquakes in Central and Eastern United States.

Detailed seismic tomography studies along the eastern shore of the Sea of Japan and near the source zone of the 2001 Bhuj earthquake in India show that, with detailed data and improved analytical techniques, it is possible to delineate the structural features of the seismic zones and test our ideas and models of the genesis of these earthquakes and to formulate new approaches. For most seismic zones, such detailed information is lacking. The results of investigations presented here also help to raise questions about the validity of our current methods of investigation and illuminate the need to develop new ones. This chapter is divided into three parts that address the current ideas that have been confirmed by the results of these studies; those that have been contradicted and what new insights have been gained; and suggestions for future studies.

13.1 Observations that support earlier ideas

Sykes (1978) first suggested that there is a global pattern of intraplate earthquakes. Subsequently, several investigators recognized that intraplate earthquakes preferentially occur in old rift structures and along craton boundaries (Mooney *et al.*, 2012). The various examples presented in this book have confirmed these ideas. Ziegler (1987) and Zoback

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(1992) suggested that mid-plate deformation resulted from stresses that originated at plate boundaries and were transmitted through the lithosphere. Numerical modeling (Chapter 10) has confirmed this premise.

Some of the earlier models in the 1970s and 1980s hypothesized that intraplate earthquakes occurred as a result of stress build-up on discrete structures in the upper and lower crust. These models were combined into a testable, unified model that postulates that these discrete structures act as local stress concentrators, a concept that was confirmed at two locations with the results of seismic tomography analysis. A comparison of Figures 6.3 and 9.5, which show the modeled structures at the Sea of Japan and Kutch Rift Basin, with Figure 11.3c, which shows the predictions of the unified model, illustrates this point. Such detailed information about the seismic structures is lacking in other regions. As newer and better data become available, this model will be tested and other models will evolve.

13.2 New observations

The temporal and spatial pattern of large historic and prehistoric earthquakes in China (Chapter 5) and the Kutch Rift Basin (Chapters 6 and 11) show an absence of repeat earthquakes on the same fault. In each case the earthquakes jumped from one location to another and were described as "roaming earthquakes" (Chapter 5). Although the spatial extent was different in these cases – widespread, continental scale in China and within a single Kutch Rift Basin in India – there was no evidence of repeat earthquakes. A similar pattern was observed for the morphogenic earthquakes (prehistoric events detected from paleo-seismological studies) in Australia (Chapter 2). These observations are consistent with a model that hypothesizes sequential reactivation on different structures. This lack of stationarity of the seismic source on a particular fault in an intraplate setting is at odds with the basic assumption of stationarity in probabilistic seismic hazard estimation methodology, which was developed for plate boundary earthquakes (Chapter 12). This dichotomy requires a reassessment of methods of seismic hazard estimation in intraplate settings and the development of new ones.

In mid-plate regions there should perhaps be a lower magnitude threshold used in seismic hazard estimation, as advocated by the authors of Chapters 4 and 8. They point out that because of low seismic-wave attenuation in mid-plate regions, the presence of poorly constructed buildings, and vulnerable local soil conditions, there may be significant damage potential due to earthquakes with magnitudes as low as 4.5.

The seismicity and geodetic observations in the decade following the 2001 M 7.7 Bhuj earthquake provide a unique dataset to study the seismogenesis of an intraplate earthquake. There was evidence of a migration of a seismic pulse away from the source of the 2001 event, reaching 250 km in about 10 years with a sequential activation of faults along the way. Monitoring of ground motion led to the detection of local, isolated pockets (hundreds of kilometers) of elevated strain rates 6 to 8 years after the 2001 earthquake. These anomalous pockets of elevated strain-rate build-up provide evidence that the spatial and temporal pattern of strain accumulation is different from that for plate boundaries.

To explain some of our current observations, different elements of earlier models were integrated into a unified model for intraplate earthquakes (Chapter 11). In this simple, testable model stresses can accumulate at local stress concentrators and react with, as well as locally rotate, the maximum horizontal stress direction. Seismic tomography has made it possible to identify these stress concentrators (Chapters 6 and 9). These local stress concentrators are of different kinds and of diverse sizes, varying from tens to hundreds of kilometers across (Figure 11.3c). Compressional jogs between en echelon faults also act as stress concentrators and have been identified in regions of large earthquakes, e.g., in the New Madrid seismic zone (Figure 7.10), the Kutch Rift Basin (between KMF and NWF in Figure 6.13) and in the Middleton Place Summerville Seismic Zone of the 1886 Charleston earthquake (Talwani and Dura-Gomez, 2009). The local stress build-up can, in some cases, be associated with a detectable rotation of the local maximum horizontal stress direction (Chapter 11). Future studies need to be designed to test this model and seek additional evidence for the local stress concentrator and the associated rotation of S_{Hmax}.

13.3 Future studies

The role of fluids as weakening agents was not addressed in this book. However, the presence of fluids has been detected by seismic tomography near two source zones (Chapters 6 and 9), and its role in the seismogenesis of intraplate earthquakes merits further study.

The unified model (Chapter 11) is based on a synthesis of current ideas and observations. It provides a framework for studying intraplate earthquakes. Both field studies and theoretical modeling are needed to test its viability and predictability. As additional and more focused data become available, new and better models will evolve to explain the phenomenon of intraplate earthquakes. How new data can help this evolution is shown by the following example.

A few years after the 2001 Bhuj earthquake, the large coseismic strain rates had returned to their background levels. More than 6 years after the mainshock, two earthquakes with magnitudes 4.1 and 4.7 occurred just south of the Kutch Mainland fault (KMF in Figure 6.13), about 25 to 30 km southwest of the 2001 earthquake. InSAR data collected between 2004 and 2007 and between 2007 and 2010 detected a local pocket of elevated vertical strain rate (16–27 mm/yr) in about a 200 sq. km area surrounding the 2007 epicenters (Figure 6.17). Does this pocket of increased strain rate surrounding the M 4+ epicenters signify that stresses are building up on a new, hitherto unidentified local stress concentrator and the potential location of a larger future earthquake? To test this idea, an array of additional GPS receivers and seismometers are being deployed in the vicinity of the region of increased uplift rate. This example shows that with further improvements in instrumentation and analysis techniques and with detailed, focused, complementary seismological and geodetic measurements, it may become possible to routinely detect potential locations of moderate to large intraplate earthquakes.

As intraplate earthquakes jump from one fault to another and there is an absence of a stationary source, we need to revise our strategies for studying them and for estimating the attendant seismic hazard. A new set of questions need to be addressed. Do we abandon the probabilistic seismic hazard analysis approach and are deterministic site-specific investigations the correct approach in estimating seismic hazards in intraplate regions? Do we examine the entire rift structure and look for local stress concentrators, or do we need to focus our efforts on areas of past large historical earthquakes?

Mooney *et al.* (2012) showed that in addition to old rift structures, many intraplate earthquakes are located near craton boundaries. Dedicated field studies are needed to identify the responsible seismic sources. A possible starting point may be based on Ziegler's (1987) observation that, in mid-plate regions, deep faults that extended to lower crustal depths are likely to be reactivated by the stresses originating at plate boundaries. Identification of such faults by geological and/or geophysical studies would be a good starting point for further investigations of the potential seismic source zones associated with craton boundaries.

Future theoretical studies could address the reasons why large earthquakes do not recur on the same fault but instead jump around, suggesting that after an earthquake most of the built-up seismic energy is expended, while at other locations it continues to build until the next earthquake. The observation of "roaming" or "wandering" earthquakes also suggests the presence of several potential stress concentrators that are sequentially reactivated. Theoretical studies are needed to estimate the magnitude of the stresses that accumulate at different stress concentrators and mechanisms to explain their temporal and spatial behavior.

The maximum magnitudes (M_{max}) of intraplate earthquakes vary from region to region. For example, in Western Europe it is rare to observe an earthquake with $M > 5$, or in Brazil with $M > 6$. Several earthquakes with $M_{max} > 6$, however, have occurred in Australia and Eastern Canada. Considerably larger earthquakes have been observed in northern China, the New Madrid seismic zone and in the Kutch Rift Basin. What controls M_{max} in intraplate regions? Along plate boundaries, M_{max} is related to the fault length, a correlation not seen in intraplate regions. Modeling suggests that M_{max} is related to the amount of stress that can build up on a stress concentrator, which in turn depends on the kind of stress concentrator present. Historically, shallow plutons have been associated with $M_{max} < 5$ and rift pillows with $M_{max} < \sim 5.5$. As mentioned earlier, for the larger earthquakes in the New Madrid seismic zone, Kutch Rift Basin, and in the source zone for the 1886 Charleston earthquake, M_{max} appears to be related to the width of the compressional step between the en echelon faults associated with the source zone. This speculative association needs to be confirmed with data from other source zones and by numerical modeling.

The diverse studies described in this book represent a step forward in our understanding of intraplate earthquakes. While they answer some questions about our understanding, they also raise many others that should be the focus of future research.

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