Cambridge University Press & Assessment
978-1-107-04038-0 — Intraplate Earthquakes
Edited by Pradeep Talwani
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Introduction

PRADEEP TALWANI

The study of intraplate earthquakes began after the development of plate tectonics theory, which explains the genesis of more than 95% of the global seismic energy release. I use a more liberal definition of intraplate earthquakes as those that occur within a tectonic plate away from a plate boundary as contrasted with the more restrictive stable continental interiors (Johnston, 1989), thereby including earthquakes in locations such as the Sea of Japan. Because of the rarity of large destructive intraplate earthquakes, a great disparity in the local geological conditions where they occur, and the wide variation in the efforts made to study them in different parts of the world, our understanding of their nature has been slow to evolve. However, in the past four decades great progress has been made in monitoring of seismicity globally, as well as in diverse approaches to their study, suitable for local geological and logistical conditions. This book is an attempt to improve our understanding about the nature of intraplate earthquakes by bringing together the results of recent advances. The different chapters in the book, written by experts in their fields, are designed in such a way that each describes a different element of the phenomenon. Together they contribute to a more integrated understanding of intraplate earthquakes.

This book describes intraplate earthquakes in eight regions of the world – from Australia, with a relatively low level of seismicity and a short historical record, to China, with a three millennia long history of destructive earthquakes. It covers regions with moderate seismicity (Western Europe and Brazil), New Madrid in the Central United States with a record of large historical earthquakes, and currently active areas of Eastern Canada, the eastern margin of the Japan Sea and Kutch, in Western India. The results of numerical modeling described in one chapter show how these mid-plate earthquakes occur in response to stresses emanating from plate boundaries. Another chapter presents a unified model to explain how these stresses build up on discrete structures and lead to such mid-plate earthquakes. Our changing views in approaches to seismic hazard analysis and conclusions and insights gained from the various chapters are discussed in the final two chapters.

Compared with the other intraplate regions, the historical record of seismicity in Australia spans little more than two centuries, and the instrumental record of seismicity extends

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over a quarter of that time. Therefore, for planners responsible for estimating seismic hazards, the concern is whether this short record of historical and instrumental seismicity including twenty earthquakes of $M > 6.0$ and seven with surface rupture is truly representative of the long-term behavior of the seismogenic structures in the continent. Because of a paucity of dense seismic networks, the earthquake locations are not well constrained, and a very small fraction of the estimated depths are accurate enough to make tectonic associations, thus limiting the ability to accurately identify and outline the buried seismogenic features.

Clark, McPherson, and Allen (Chapter 2) solve the problem of a short historical and poorly constrained seismicity record by using a well-preserved geological record to extend the prehistorical record of past earthquake activity to more than 10 Ma. They note, “Australia is one of the lowest, flattest, most arid and slowly eroding continents on Earth. Accordingly, large parts of Australia are favorable for the preservation of tectono-geomorphic features, such as fault scarps, for tens of thousands to millions of years.” They use a two-pronged approach in their search for records of paleo and historical (collectively, morphogenic) earthquakes that have ruptured faults during the past millennium. A geomorphological study based on aerial photographs was used to select sites and disruption localities for the second phase of the investigations, which involves trenching for paleoseismological investigations. Evidence of more than 300 fault scarps and other geomorphic features dating back to more than 10 Ma was found in the geological record.

Based on the geology and crustal setting, the authors recognized six neotectonic domains in Australia. For each of those, they analyzed the geomorphic features based on their fault length and vertical displacement. They interpreted the results in terms of seismological parameters such as the maximum magnitude, earthquake frequency, and the temporal pattern of the occurrence of morphogenic earthquakes in different neotectonic domains. They conclude that the catalog of historical seismicity significantly underestimates the large earthquake potential in the continent.

Brazil spans most of the mid-plate area in South America and little has been published on the seismicity characteristics of this large, stable continental region. Two magnitude 6 earthquakes are the largest events in the revised catalog of historical events (from about mid nineteenth century) and instrumental data (mainly from the past 60 years). Assumpção and colleagues (Chapter 3) discuss the distribution of seismicity and possible correlations with the main geological provinces and geophysical features. Despite the short period of the catalog, which may not be representative of the long-term seismicity (paleoseismological studies, for example, indicate magnitudes could reach 7, based on liquefaction features in northeastern Brazil), interesting correlations have been found. A trend of higher seismicity was found in areas presumed to have thinned lithosphere, as also near craton edges (around craton keels), even for magnitudes down to 3.5, similar to global correlations for larger earthquakes. Also, the continental shelf is more seismically active than the average intraplate region, even for low magnitudes. Flexural stresses associated with gravity highs were also found to be an important factor in helping explain Brazilian intraplate seismicity. The new multidisciplinary Brazilian dataset should provide a basis for comparisons with other intraplate regions and to test models developed in other continents.

Accurate determination of the nature and configuration of seismogenic structures responsible for the seismic hazard of a region is particularly important, especially when it includes highly populated locations. Such is the case in Eastern Canada where the metropolitan areas of Ottawa, Montreal, and Quebec all lie in the St. Lawrence Rift System (SLRS), the most active seismic region in eastern North America. Lamontagne and Renalli address this issue in Chapter 4. The NE–SW-trending SLRS, which extends for more than ~1,200 kilometers, is a failed paleo-rift and attached to it are the NW–SE-oriented aulacogens, the Ottawa–Bonnechère and the Saguenay grabens. The structure of the SLRS is further complicated by a Devonian age, 50 to 60 kilometers broad meteor impact structure lying over the SLRS and centered around Charlevoix. The impact structure has further shattered the rocks in the SLRS and produced cross faults.

The authors use an integrated approach in assessing the seismic hazard for this region – critical to the Canadian economy. Starting with historical accounts of European settlers in the seventeenth century, there is evidence of several M > 6.0 earthquakes in the SLRS. Instrumentally recorded seismicity identified three main seismic zones: the Charlevoix seismic zone along the SLRS, the northwest-trending Western Quebec seismic zone, and the Lower St. Lawrence seismic zone. Outside these zones there is low-level background seismic activity. Most of the hypocenters are located in the middle to upper lower crust, although a deeper event (~29 km) did occur in the Saguenay graben in 1989. Traditionally, the seismic hazard has been associated with larger events in the rift structure. However, the authors argue that moderate events with M > 4.5 can also pose a seismic hazard because of low attenuation, thick unconsolidated post-glacial marine clay soils that amplify ground motions, and the presence of old buildings in these zones. They suggest that most of the moderate earthquakes are associated with local causes rather than with the rift structures and such causes should be considered in evaluating the hazard. They identify these as locally weakened faults, elevated pore pressures, and local variations in the stress level.

In the past decade, as newer and better seismicity data began to accumulate, questions emerged regarding the stationarity of seismicity in intraplate regions, a common assumption in the practice of seismic hazard analysis carried over from studies of interplate regions. In most intraplate regions, the historical data and sporadic paleoseismological investigations are inadequate to accurately describe the spatiotemporal pattern of past seismicity needed to assess the assumption of stationarity of seismic sources. In Chapter 5, Liu, Wang, Ye, and Jia address this question in their study of the intraplate earthquakes of North China.

On a continental scale, North China is one of the most seismically active regions in the world, with a historical record of more than 3,000 years. These records document more than 100 large (M > 6) earthquakes in the past 2,000 years, including the world's most catastrophic M ~ 8.3 1556 Xuaxian earthquake with a death toll of 830,000 victims. Liu *et al*. describe the spatiotemporal pattern of the historical seismicity and, using the results of intensive geological, geophysical, seismological, and GPS investigations in the past decades, relate the significant earthquakes to specific structures. They show that no M ≥ 7.0 event ever ruptured the same fault segment twice in the past 2,000 years, and there was “roaming” of large earthquakes between widespread fault systems. Their results demonstrate the complex spatiotemporal patterns of intraplate earthquakes, the problems of long recurrence time and short and incomplete records, and the need for a reassessment of seismic hazard in intraplate regions.

The largest and best studied intraplate event in the past two decades is arguably the January 26, 2001 M 7.7 Bhuj earthquake in Western India. Soon after the earthquake, scientists from several institutes carried out detailed aftershock studies. In the past 10 years, additional deployment of large arrays of seismograph and GPS receivers has been complemented with intensive geophysical and geological investigations providing an incredible modern-day dataset. In Chapter 6, Rastogi, Mandal, and Biswas summarize the results of these multidisciplinary investigations, providing for the first time an opportunity to study the seismogenesis of a major intraplate earthquake. Using seismicity and seismic tomography data they show that the earthquake nucleated at midcrustal depths in the vicinity of a large, high-density, mafic body, in parts of which were pockets of fluids. The large stress drop associated with it spawned a stress pulse that travelled at 25 km/yr. This stress pulse, together with coseismic stress field changes, led to a sequential activation of multiple faults, both to the north and to the south of the epicenter, producing 20 M 4 to 5.1 earthquakes up to a distance of ~250 km. The most distant M 5 earthquake occurred in 2011. GPS and InSAR studies revealed that, after the dissipation of the coseismic strain in the first few years after the mainshock, the horizontal strain returned to a background value of ~2–5 mm/yr. However, InSAR and GPS surveys, 7 to 10 years after the mainshock, provided evidence for localized pockets of high vertical strain rates located in the vicinity of faults that had been activated by the seismicity that followed the 2001 mainshock. Insights gathered from this contemporary study of a major earthquake can be used to analyze the sparse data surrounding older intraplate earthquakes.

Arguably, the St. Lawrence Rift System in Eastern Canada and the New Madrid seismic zone (NMSZ) in the Central United States are the most active seismic zones in eastern North America and also the best studied. After a series of M ~ 7 earthquakes in 1811–1812, the continuing seismicity in the NMSZ has been at a lower magnitude level, and the contemporary seismicity rarely exceeds M 4. The NMSZ has also been a subject of intense, dedicated studies in the past few decades. Although the NMSZ is one of the best studied cases of intraplate earthquakes, there is an absence of consensus about its cause and the contemporary seismic hazard that it poses.

In Chapter 7, Van Arsdale presents a summary of these investigations, including a detailed geological history of the region, and the results of historical and contemporary seismological and paleoseismological investigations. Additional studies that are reviewed include GPS, geophysical, and geological investigations. These abundant data have spawned a plethora of explanations, models, and speculations about the nature of the seismic hazard in the NMSZ. Van Arsdale carefully presents these often conflicting explanations and how they impact our current assessment of the seismic hazard. One of the suggestions based on geological data is that the contemporary seismicity began in the Holocene, and that the current GPS data indicate very low strain rates and a general absence of a major seismic hazard: a conclusion potentially at odds with the paleoseismological record and alternative explanations of the GPS data. Currently, these data have been explained from a local perspective. I anticipate that new explanations and models will emerge when these assorted studies are evaluated from the global perspective described in this book.

In Western Europe, large earthquakes have been few and far between, but, when they did occur, even the moderate ~M 5 events left a long-lasting impression. In Chapter 8, Camelbeeck and co-authors present a method of quantitative assessment of the seismic hazard based on a detailed evaluation of the hazard caused by past earthquakes, especially those in the past decade. They use the damage caused by past earthquakes as an important source of information about future seismic vulnerability of a region. They use a computerized, rich archival database that includes heritage records about the architectural style and kind of building – church, castle, or ordinary home – the construction style and material, and information about the underlying soils, to develop a seven-point “damage characteristics” scale. They illustrate their methodology with an evaluation of the damage following the Central Belgium earthquake of 1828. Their results show that, in other intraplate regions where detailed macroscopic data are available for the rare, moderate earthquake, it is possible to assess the vulnerability and potential seismic hazard to a region posed by future earthquakes.

Although a spatial association of intraplate earthquakes with rifts has long been suggested, the identification of a causal seismogenic structure within the rift has so far proved elusive because of a lack of detailed seismicity, geological, and geophysical data. In Chapter 9, Kato describes the results of using a dense seismic network deployed immediately after three large intraplate earthquakes along the eastern margin of the Japan Sea. Analysis of the seismicity data together with detailed seismic tomographic studies led to the discovery of a buried rift with stepwise and tilted block structures, together with a buried rift pillow in the lower crust with associated weakening fluids. The seismicity was caused by the reactivation of the pre-existing faults within the ancient rift system. The rift pillow appears to have acted as a stress concentrator, and the fluids as weakening agents. The identification of the seismogenic features responsible for the M 6+ earthquakes provided validation of models suggested for the genesis of these intraplate earthquakes.

A significant percentage of intraplate earthquakes are associated with ancient rift zones and occur hundreds to thousands of kilometers from plate boundaries. One of the important questions is explaining the source(s) of stresses that are responsible for their occurrence. Nielsen, Stephenson and Schiffer address this question in Chapter 10. They note that the locations of the intraplate earthquakes in Western Europe are also the locations of stress inversion of rift basins. They use numerical thermo-mechanical models of stress inversion of basins to show that these intraplate earthquakes in Western Europe result from the interaction of the stresses transmitted from plate boundaries through the lithosphere and the perturbing “potential energy” stresses. These potential energy stresses are derived from models of lateral variation in the present-day density structure of the lithosphere, and lateral pressure variations in the mantle below the lithosphere due to density contrasts

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and related convection. They show that the main source of intraplate stress is that derived from plate boundaries, and "primary inversion" occurs only when it combines favorably with potential energy stresses in combination with the existence of favorably oriented pre-existing lithosphere-scale weaknesses.

Talwani (Chapter 11) presents a unified model, based on an integration of the results of earlier studies aimed at explaining how stresses transmitted from plate boundaries cause intraplate earthquakes. These stresses were found to cause local stress accumulation on discrete structures, which were identified as local stress concentrators. These local stress concentrators are located in both the upper and lower crust within the rift, and their reactivation occurs in the present-day compressional stress field in the form of earthquakes. Commonly observed local stress concentrators are favorably oriented (relative to the regional stress field) fault bends and fault intersections, flanks of shallow plutons, buried rift pillows, and restraining stepovers. Stress build-up associated with one or more local stress concentrators interacts with and produces a potentially detectable local rotation of the regional stress field with wavelengths of tens to hundreds of kilometers. A local rotation of the regional stress field provides evidence of local stress increase and thus potentially suggests the location of future intraplate earthquakes. This model provides a framework for potentially testing for and assigning the cause of intraplate earthquakes at other locations in the world.

One of the important elements in the study of earthquakes in any region is to assess the potential seismic hazard posed by future earthquakes. The traditional approach used in intraplate regions, especially in the construction of critical facilities, is probabilistic seismic hazard analysis; a methodology imported from plate boundary regions. As better seismicity and other data become available for intraplate regions, it is becoming apparent that some of the assumptions on which the standard seismic hazard analysis is based may not be valid for intraplate regions, especially the assumption of stationarity of the seismic source. Hough (Chapter 12) discusses the problems of applying the standard seismic hazard methodology in the case of the Central and Eastern United States, especially in the case of the New Madrid seismic zone. Among some of the problems noted by Hough are that GPS results show little or no resolvable deformation in the source zones, and paleoseismological evidence suggests large Holocene and late Pleistocene earthquakes in other regions. In addition, there is evidence for short-term temporal clustering of seismicity with longer-term migration, and estimating earthquake rates from short historical records is also problematic. The results of this study serve as a warning to scientists and engineers tasked with assessing seismic hazards in intraplate regions about the wisdom of using standard probabilistic seismic hazard analysis in intraplate regions.

In the final chapter, Talwani presents a synthesis of conclusions from a study of the chapters in this book. These new data and case histories from different parts of the world support earlier ideas of a global pattern in the location of the larger intraplate earthquakes in old rift structures. Various case histories show evidence that large earthquakes do not recur at the same locations but in fact jump from one fault to another. The different chapters illustrate both the similarities and the differences in the nature of intraplate earthquakes in different parts of the world and located in different geological terranes. The chapter concludes with lessons learnt and suggestions for future studies.

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2

Intraplate earthquakes in Australia

DAN CLARK, ANDREW MCPHERSON, AND TREVOR ALLEN

Abstract

Relative to other intraplate areas of the world, Australia has a short recorded history of seismicity, spanning only a couple of centuries. As a consequence, there is significant uncertainty as to whether patterns evident in the contemporary seismic record are representative of the longer term, or constitute a bias resulting from the short sampling period. This problem can, in part, be overcome by validation against Australia's rich record of morphogenic earthquakes – Australia boasts arguably the richest late Neogene to Quaternary faulting record of any stable continental region. Long-term patterns in large earthquake occurrence, both temporal and spatial, can be deduced from the landscape record and used to inform contemporary earthquake hazard science. Seismicity source parameters such as large earthquake recurrence and magnitude vary across the Australian continent, and can be interpreted in a framework of large-scale neotectonic domains defined on the basis of geology and crustal setting. Temporal and spatial clustering of earthquakes is apparent at the scale of a single fault, and at the 1,000 km scale of a domain. The utility of the domains approach, which ties seismicity characteristics to crustal architecture and geology, is that behaviours can be extrapolated from well-characterised regions to poorly known analogous regions, both within Australia and worldwide.

2.1 Introduction

The Australian continent resides entirely within the Indo-Australian Plate, and is classified as a Stable Continental Region (SCR) in terms of its plate tectonic setting and seismicity (Johnston *et al.*, 1994; Schulte and Mooney, 2005). Such settings host approximately 0.2% of the world's seismic moment release (Johnston, 1994), and moderate to large earthquakes are rare. Analysis of focal mechanisms from SCR crust (Zoback, 1992;

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Reinecker *et al.*, 2003; Schulte and Mooney, 2005) indicates that compressive stress regimes dominate within continental interiors, with maximum compressive stresses oriented predominantly in accordance with absolute plate motion (see also Richardson, 1992). Australia is anomalous in this respect. While earthquake focal mechanisms suggest that the crustal stress field at seismogenic depths in Australia is everywhere compressive, with significant strike-slip components along the northwest margin (NWSSZ, Figure 2.1) and in the Flinders/Mount Lofty Ranges (FRSZ, Figure 2.1) (Leonard *et al.*, 2002; Clark *et al.*, 2003), stress orientations in southern Australia are typically not parallel to the north–northeast-directed plate motion vector (Coblentz *et al.*, 1995; Hillis and Reynolds, 2000, 2003; Sandiford *et al.*, 2004, 2005; Hillis *et al.*, 2008).

In the southern half of the continent, the maximum horizontal stress orientation (S_{Hmax}) is essentially east–west in western and central Australia and rotates to northwest–southeast in eastern Australia (Figure 2.1). In the northern half of the continent, the stress field transitions from the generally east–west trend in the south, to a broadly northeast–southwest trend. To a first order these regional stress orientations are not influenced by tectonic terrane, crustal thickness, heat flow, regional structural trends, geological age, or by the depth at which orientations are sampled (e.g., Hillis *et al.*, 2008; Sandiford and Quigley, 2009; Holford *et al.*, 2011). The trends have been satisfactorily modelled in terms of a balance between plate driving and resisting torques generated at the margins of the Indo-Australian Plate (Cloetingh and Wortel, 1986; Coblentz *et al.*, 1995, 1998; Reynolds *et al.*, 2002; Burbidge, 2004; Sandiford *et al.*, 2004; Dyksterhuis and Müller, 2008) (Figure 2.2).

Stratigraphic relationships establish that fault-related and presumably seismogenic deformation consistent with the present stress field commenced in the late Miocene, in the interval 10–6 Ma (Dickinson *et al.*, 2002; Sandiford *et al.*, 2004; Keep and Haig, 2010), as the result of complex evolving plate boundary conditions (Sandiford and Quigley, 2009). It has been proposed that the onset of deformation at specific locations may reflect rising stress levels related to the combination of all plate boundary forcings (Sandiford and Quigley, 2009), with variations in the thermal structure of the Australian lithosphere influencing the localisation of deformation at the regional or terrane scale (e.g., Celerier *et al.*, 2005; Sandiford and Egholm, 2008; Holford *et al.*, 2011). Analysis of the spatial and temporal patterns of contemporary seismicity might therefore be improved by studying the extraordinarily rich Neogene to Quaternary record of seismicity in the Australian landscape (e.g., Clark *et al.*, 2012). In the sections that follow, earthquake occurrence in Australia is therefore examined from both the historic and prehistoric (Neogene and Quaternary) records.

2.2 Two centuries of earthquake observations in Australia

Between 1788, when European colonists reported the first earthquake felt in Australia (Historical Records of Australia, 1914), and the early 1900s, newspaper articles were the main source of information about earthquakes (e.g., Malpas, 1991), and continued to be important until the 1960s (McCue, 2004). The first seismographs in Australia for

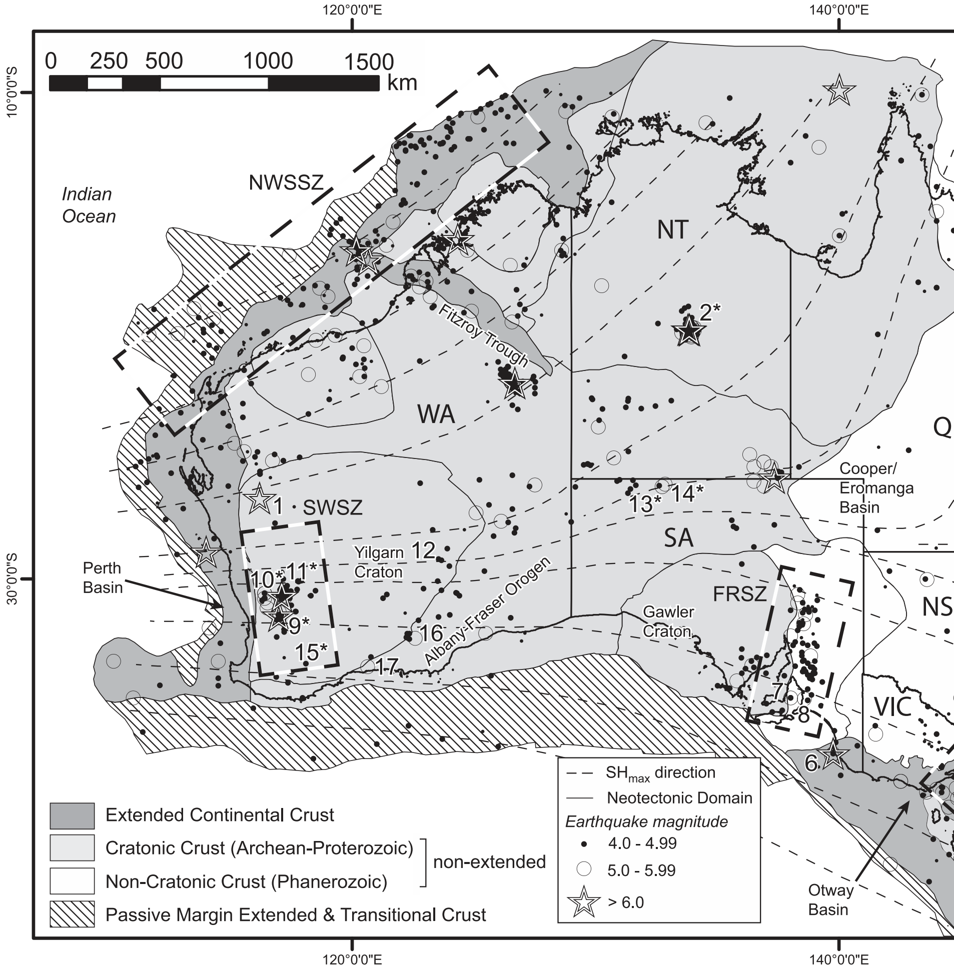

Figure 2.1 Map of the Australian continent plotting historical seismicity from the complete Australian catalogue for earthqua
shown: SWSZ, Southwest Seismic Zone; NWSSZ, Northwest Shelf Seismic Zone; FRSZ, Flinders Ranges Seismic Zone; SE
earthquakes or earthquake sequences mentioned in text are indicated by numbers: 1, Meeberrie; 2, Tennant Creek; 3, offshore n
Newcastle; 6, Beachport; 7, Warooka; 8, Adelaide; 9, Meckering; 10, Calingiri; 11, Cadoux; 12, Kalgoorlie-Boulder; 13, Erna
16, Norseman; 17, Ravensthorpe; 18, Mount Hotham. Numbers with asterisks indicate confirmed surface-rupturing earthquake
direction is indicated by fine dashed lines. The continent is broadly divided on the basis of geology and tectonic history, showin
crust in the central and western parts, non-extended non-cratonic crust in the east, and extended crust around much of the conti