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Characterizing Seismicity in Alberta for Induced-Seismicity Applications

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A thesis submitted in partial fulfillment of the requirements for the Master of Science degree in Geophysics

CHARACTERIZING SEISMICITY IN ALBERTA FOR INDUCED-SEISMICITY APPLICATIONS

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by

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Abstract

This report documents the compilation of a high-quality catalog of earthquakes in Alberta and the surrounding region: the Composite Alberta Seismicity Catalog (CASC). It currently includes events through July 2015. The catalog and its documentation are available for download at www.inducedseismicity.ca. For the determination of the magnitude of completeness (M_c) of the catalog, we map M_c (x_i, y_i, Δt) across a grid of the region, where x_i and y_i represent the longitude and latitude of center nodes in the grid and Δt indicates time period. The empirical relation determined from the catalog and station data is of the form $M_c(D_4) = aD_4+c$, where D_4 is the distance from (x_i, y_i) to the fourth-nearest station. Seven M_c maps are created to represent spatial variations of M_c from 1985 to 2015. Based on the derived M_c maps, we estimate the equivalent rate of occurrences of **M** ≥3 earthquakes in various grids.

Keywords

Composite Alberta Seismicity Catalog (CASC), Magnitude of Completeness (M_c), Seismicity rates

Co-Authorship Statement

This thesis is prepared in integrated-article format and includes the following manuscripts written by Luqi Cui and the co-authors. Luqi is the first author on studies of the composite Alberta seismicity catalog (CASC), its magnitude of completeness and related statistical analyses. Luqi performed the analyses described in this thesis and authored these reports with assistance from the co-authors. The CASC during the post- 2013 years was compiled by Dr. Azadeh Fereidoni and is explained by Luqi in this thesis.

1) Cui, L., Fereidoni, A., Atkinson, G.M. (2015). Compilation of Composite Alberta Seismicity Catalog (CASC) with application to induced-seismicity hazard in Alberta, unpublished report. www.inducedseismicity.ca

2) Cui, L., Atkinson, G.M. (2015). Spatiotemporal variations in the Completeness Magnitude of the Composite Alberta Seismicity Catalog (CASC), manuscript submitted to Seismological Research Letters.

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Table of Contents

List of Tables

List of Figures

List of Appendixes

List of Abbreviations

CASC	Composite Alberta Seismicity Catalog
IRC	NSERC/TransAlta/Nanometrics Industrial Research Chair
NSERC	Natural Sciences and Engineering Research Council
M_c	magnitude of completeness
x_i	longitude of the center node in grid i
y_i	latitude of the center node in grid i
Δt	a time period
D_4	distance from (x_i, y_i) to the fourth nearest station
M or MW	Moment magnitude
RMH	Rocky Mountain House
CL	Crooked Lake
HF	hydraulic fracturing
GSC	Geological Survey of Canada
AGS	Alberta Geological Survey
ANSS	Advance National Seismic System
ML	Local magnitude
MN	Nuttli magnitude
MD (Md)	Duration magnitude
Mb (MB)	Teleseismic body-wave magnitude
MS	Surface-wave magnitude
CASC13	Composite Alberta Seismicity Catalog from 1906 to 2013
CASC14x	Composite Alberta Seismicity Catalog 2014 forward

NMX	Nanometrics Inc.
CCSC	Canadian Composite Seismicity Catalog
NCEDC	Northern California Earthquake Data Center
CNSN	Canadian National Seismograph Network
ATSN	Alberta Telemetered Seismograph Network
CRANE	Canadian Rockies and Alberta Network
MRSN	Montana Regional Seismic Network
US-REF	The United States Reference Network
RAVEN (RV)	Regional Alberta Observatory for Earthuqake Studies
TD	TransAlta Dam Monitoring
IRIS	Incorporated Research Institutions for Seismology
SHEEF	Seismic Hazard Earthquake Epicentre File
POLARIS	Portable Observatories for Lithospheric Analysis and Research Investigation Seismicity
B.C.	British Columbia
UTC	Coordinated Universal Time
G-R	Gutenberg-Richter
FMD	Frequency magnitude distribution
MAXC	Maximum Curvature method
GFT	Goodness-of-fit method
EMR	Entire magnitude range method
MBS	M_c by b-value stability method
μ	The magnitude at which 50% of the earthquakes can be detected
σ	Standard deviation

M_{co}	Cut-off magnitude
c_1	The increase in D_4 per magnitude unit
c_2	The distance to the fourth nearest station to locate an event of magnitude of zero

Chapter 1

1 Introduction and Study Motivation

1.1 Study Motivation

The occurrence of earthquakes that are triggered by industrial processes including mining, oil and gas productions, dams and other energy technologies is called induced seismicity (Ellsworth, 2013; Atkinson et al., 2013). It has become a pressing and timely problem in western Canada including Alberta and British Columbia, especially due to increasing gas and oil production, wastewater disposal and hydraulic fracturing operation (Baranova et al., 1999; BC Oil and Gas Commission, 2012, 2014; Farahbod et al., 2015; Horner et al., 1994; Milne, 1970; Schultz et al., 2014, 2015b). The potential earthquake sources, the magnitudes of earthquakes, rates of occurrences and resulting ground motions are the key parameters that determine the relative hazard from earthquakes (McGuire, 2004). In this study, I focus on issues that are key to assessing the rates of induced seismicity in and around Alberta.

1.1.1 Injection-Induced Earthquakes

Various anthropogenic applications induce seismicity and introduce new challenges for the study of hazard from earthquakes. In the Horn River Basin of British Columbia, a sequence of earthquakes with maximum moment magnitude (**M**) 3.0 and larger was reported to be caused by fluid injection during hydraulic fracturing in proximity of pre-existing faults in 2009 (BC Oil and Gas Commission, 2012). Other instances of induced seismicity, sometimes including events of **M** >4, have also been observed in recent years (Ellsworth, 2013; Holland, 2013; Schultz et al., 2015). Besides hydraulic fracturing, the disposal of wastewater into deep strata is another major cause of injection-induced earthquakes (Healy et al., 1968). Events as large as **M** 5.7 in 2011 have been associated with wastewater-injection wells in Oklahoma (Keranen et al., 2013; Ellsworth, 2013). The **M** 5.7 Oklahoma earthquake damaged buildings in the epicentral area and could be felt 1000 km away.

The aforementioned examples of induced seismicity noted that various anthropogenic activities can cause micro to moderate earthquakes in different locations. Besides hydraulic fracturing and wastewater disposal, dam impoundment, fluid extraction, enhanced geothermal systems can also trigger earthquakes (Davies et al., 2013; Schulz et al., 2015b). The assessment of the potential hazard from induced seismicity has become a critical task, particularly because seismicity rates have increased in some locations. For example, Ellsworth (2013) showed that the earthquake count increased dramatically over the past few years (Figure1-1) in the central and eastern United States. He observed more than 100 **M** ≥3 earthquakes per year from 2010 through 2012, compared with an average rate of 21 events/year from 1967 to 2000.

1.1.2 Induced Seismicity in Alberta

Unlike the clear observation of the rapid rise in seismicity rates in the central United States, in Alberta, it is harder to see a well-defined long-term seismic rate change. This is because of the prevalent data clustering in time and space, with clusters turning on and off over time, the sparse seismicity data until very recently, the presence of quiescent seismic zones, and lack of a homogeneous baseline catalogue. The appearance of several seismically active clusters (Figure1-2) in western Alberta have been noted over the years, including Fort St. John (Horner et al., 1994), Turner Valley (Ellis and Chandra, 1981), Snipe Lake (Milne, 1970), the Rocky Mountain House (RMH) (Rebollar et al., 1982, 1984; Wetmiller, 1986; Baranova et al., 1999), the Brazeau River (Schultz et al., 2014) and the Crooked Lake (CL) near Fox Creek (Schulz et al., 2015). These aforementioned clusters have been identified as potentially-induced seismicity, and include seismicity from production, wastewater injection and hydraulic fracturing.

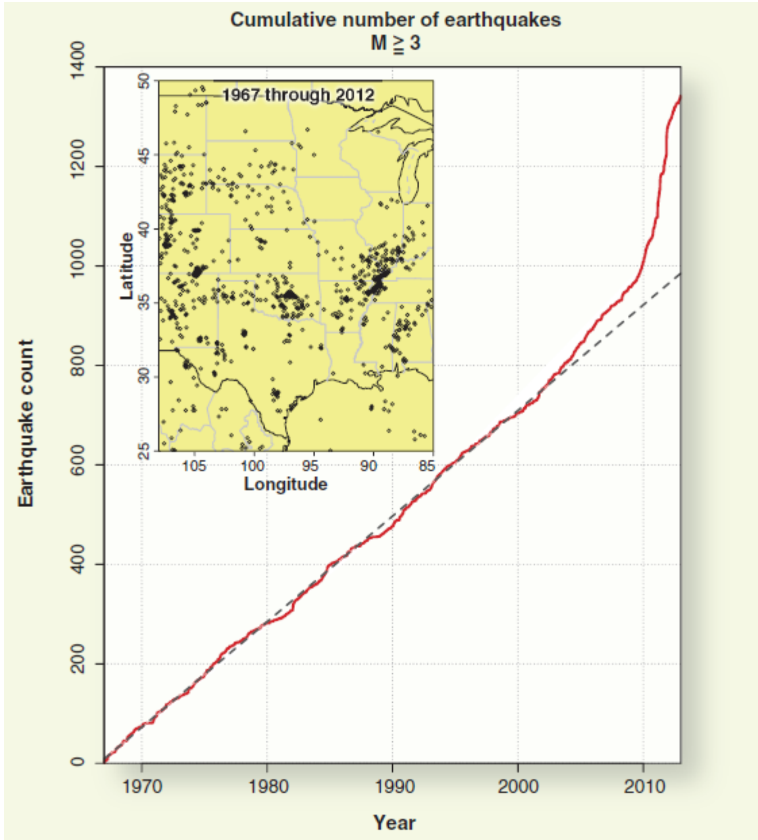

Figure 1-1: Cumulative number of earthquakes with M ≥3 in the central and eastern United States during 1967-2012. The dashed line is the long-term rate of 21.2 earthquakes/year. The insert is the distribution of epicenters in the study region (from Ellsworth, 2013).

Alberta is a transition zone from a relatively low-seismicity intraplate region to a more active foreland belt, the Rocky Mountains region, in the southwest of the province (Milne, 1970; Milne et al., 1978; Stern et al., 2011, 2013; Schultz et al., 2015). There are no historical records of any large (**M** >6) earthquakes occurring in Alberta to date, but thousands of micro to moderate earthquakes have been recorded, especially during the last five to ten years with the decreasing threshold of the magnitude of detection. As a main source of oil and gas production, thousands of shallow and deep injection and extraction wells are located in Alberta. Seismicity triggered by oil and gas operations, including hydraulic fracturing, wastewater disposal and production are of increasing concern, and the subject of much current research in western Canada like the

NSERC/TransAlta/Nanometrics Industrial Research Chair in Hazards from Induced Seismicity (IRC) Project (Atkinson et al., 2013).

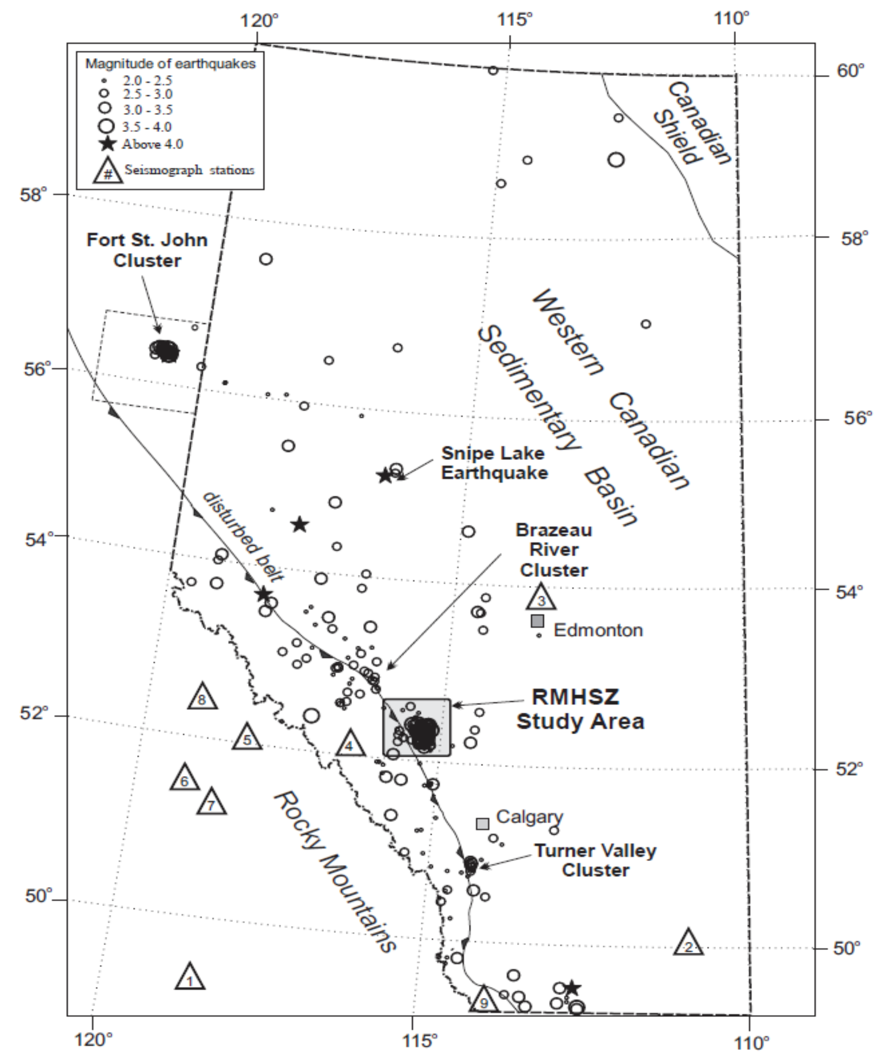

Figure 1-2: Seismic clusters in Alberta and its surrounding area. Circles represent seismic events (1957-1997); triangles represent seismograph stations (from Baranova et al., 1999).

1.2 Review of Recent Induced Seismicity Studies for Alberta

A recent issue of *Seismological Research Letters* (*SRL*, May 2015 issue) focused on various aspects of induced seismicity, including basic seismological and ground motion observations, seismic cluster studies, numerical simulation of fault activation and risk mitigation (Eaton and Rubinstein, 2015). Some of these papers demonstrate the observed changes of seismic event counts in specific areas such as RMH, which highlights the importance of having a baseline catalog that quantifies the spatial and temporal variabilities of the magnitude of completeness.

Eaton and Babaie Mahani (2015) focus on two clusters in Alberta: the RMH cluster and the CL seismicity sequence in the Fox Creek area. They re-evaluate the results of Baranova et al. (1999) and infer that in the RMH area, where seismicity has been inferred to result from volumetric changes due to gas extraction, there is ~5 years delay between the onset of production and the start of seismicity (Figure1-3). Before an **M** 3.8 event occurred in 9 August 2014, the rate of seismic activity was declining near RMH, synchronous with the decreasing rate of gas production but delayed ~ 5 years. This statistical correlation between seismic rate and gas production rate is a good example of temporal seismic rate changes.

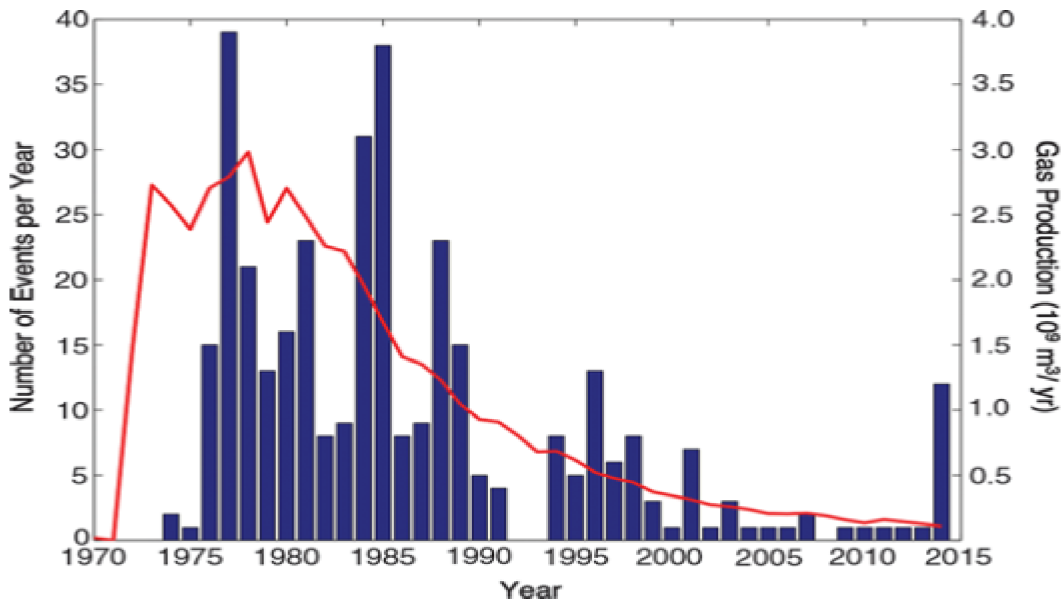

Figure 1-3: Number of earthquakes per year (blue bars) in RMH compared with gas production [m^3/yr] from the Strachan D3-A pool (red curve). (from Eaton and Babaie Mahani, 2015 (modified from Stern et al., 2013)).

Schulz et al. (2015) compare the seismicity patterns with the hydraulic fracturing (HF) operations for the Crooked Lake (CL) earthquake sequence in 2014 (Figure1-4). The consistency between HF schedules and timing of seismic activity is apparent in Figure1-4. The correlation for the timing of all subsequences of CL and suspected HF stimulations has a confidence level greater than 99.99% (Schulz et al., 2015).

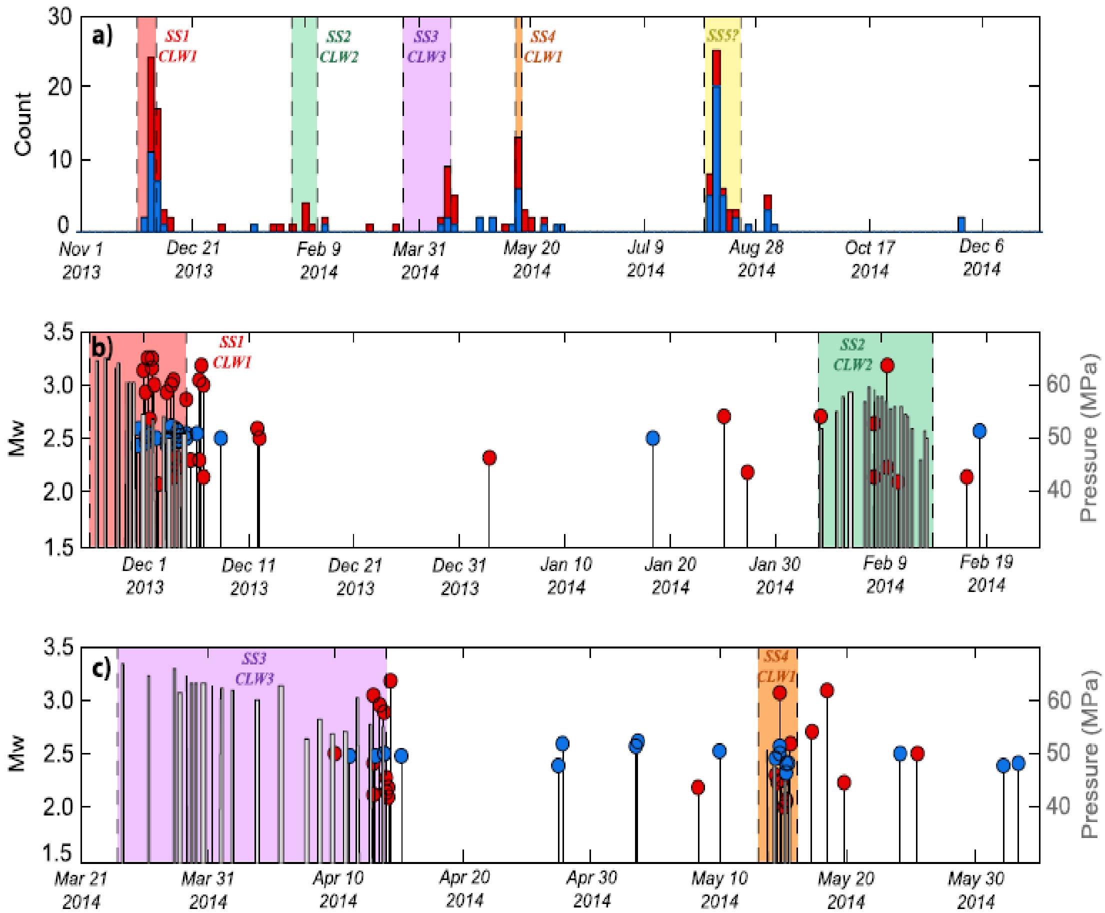

Figure 1-4: Timing of the CL earthquake sequence and hydraulic fracturing (HF) completions. The colored background with labeled subsequence and well represent HF schedules. (a) Histogram of located seismic events (red bars) and extended seismicity from cross correlation (blue bars). (b) & (c) Moment magnitudes of located (red circles) and detected (blue circles) events and average injection pressure in MPa (gray bars) during HF operation (from Schultz et al., 2015).

1.3 Motivation and Organization of Work

A prerequisite for many analyses of induced seismicity in Alberta is a comprehensive composite seismicity catalog for Alberta and its surrounding area, allowing special characterization of seismicity rates and how they have changed with time. Compilation of this catalog, the Composite Alberta Seismicity Catalog (CASC), was a key aim of this study, and is described in Chapter 2, which documents the seismic networks in the study area, the main contributing agencies and the construction of the CASC. The CASC covers the area 48°- 60° N, 110°- 124° W (Figure 2-3 and Figure 2-4). This compiled catalog provides a useful baseline for studying earthquake hazard due to induced seismicity in Alberta.

In Chapter 3, we review four methods to estimate the magnitude of completeness (M_c) and illustrate their limits for the M_c estimation in Alberta. M_c is the magnitude above which the catalog is believed to be complete, with no events missing due to sparse instrumentation (Rydelek and Sacks, 1989). A reliable estimation of M_c is required in order to assess seismic rate changes, compute magnitude recurrence parameters, and for purposes of earthquake forecasting (Mignan et al., 2011; Mignan and Woessner, 2012). It is because of the importance of M_c that a number of techniques to evaluate or map M_c have been developed.

Chapter 4 examines the spatiotemporal variations in the completeness magnitude of the CASC (Cui et al., 2015) and maps the occurrences of **M** >3 earthquakes in several relatively active areas across space and time. In this study, we employ a catalog-network-based method to map the spatiotemporal variations of M_c in Alberta. In Chapter 5, I provide a summary, discussion of the research work and suggestions for further investigation in future works.

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Chapter 2

2 Compilation of Composite Alberta Seismicity Catalog (CASC) with application to induced-seismicity hazard in Alberta[1]

2.1 Introduction

The province of Alberta, Canada, is a transition zone from a relatively low-seismicity intraplate region to a more active foreland belt, the Rocky Mountains region, in the southwest of the province (Milne, 1970; Milne et al., 1978; Stern et al., 2011, 2013; Schultz et al., 2015). While there is no historical record of any large (**M** >6) earthquakes occurring in Alberta to date (Lamontagne et al., 2007; Stern et al., 2013), there are thousands of recorded micro to moderate earthquakes. In the past decade, recorded seismicity in Alberta has increased dramatically due to both improved monitoring and an increase in seismicity rates due to induced seismicity (Stern et al., 2011; Atkinson et al., 2015). Induced seismicity is a particularly pressing issue in Alberta. Many effective practices related to oil and gas production, including hydraulic fracturing and wastewater injection, are likely to result in more earthquakes (Ellsworth 2013; Stern et al, 2013). In Alberta, significant seismic activity has been associated with hydraulic fracturing operations, particularly near Fox Creek, Alberta (Shultz et al., 2015).

A critical prerequisite for scientific analyses related to the induced seismicity in Alberta is to provide a comprehensive and homogenous seismicity catalog for the region. Currently, the seismicity data of Alberta is dispersed in different sources from several reporting agencies, including the Geological Survey of Canada (GSC), the Alberta Geological Survey (AGS) and the U.S. Advanced National Seismographic System

[1] A version of this chapter has been published online at www.inducedseismicity.ca. Cui, L., Fereidoni, A., Atkinson, G.M. (2015). Compilation of Composite Alberta Seismicity Catalog (CASC) with application to induced-seismicity hazard in Alberta, unpublished report.

(ANSS). None of these catalogs are complete, and they employ a variety of magnitude types and formats. For instance, the GSC catalog reports events in various magnitude scales including local magnitude (*ML*), Nuttli magnitude (*MN*) and moment magnitude (**M**), and these measures are not necessarily equivalent. The ANSS catalog often uses duration magnitude (*Md*). Since 2006, the AGS, in collaboration with the University of Alberta and the University of Calgary, has been adding stations and thus coverage has improved significantly in the last decade. The AGS also is compiling a catalog, from 2006 onwards, but their published information currently is available only through 2010 (Stern et al., 2011). The AGS catalog is more complete than the GSC catalog as they use more stations, but because different stations are used, the GSC and AGS solutions often differ significantly in both location and magnitude for the same event. A new network, the TD network of TransAlta/Nanometrics, began operation in 2013, adding another 29 stations. A catalog of events from this network (since 2013) is compiled in real time by Nanometrics Inc. In this study, we compile a comprehensive, high-quality and easy-to-use catalog that covers the period of historical record from 1906 to 2013, by combining information from available catalogs. We refer to this as the Composite Alberta Seismicity Catalog (CASC). The CASC provides an essential reference database for the investigation of seismicity changes due to oil and gas activities in Alberta.

The CASC contains information on felt and instrumental seismic events from 1906 to the present in the study area of 48°- 60° N, 110°- 124° W (Figure2-3 and Figure2-4). There are two time spans for the CASC: 1906-2013 and after 2014; we document the two parts as CASC13 and CASC14x. The CASC13 is a reference database compiled to the end of 2013, and is intended to be a document that does not change with time (unless new information on older events becomes available). By contrast, the CASC14x will be updated a few days after the end of each month. The CASC13 and CASC14x are in the same format and follow the same conventions, allowing users to merge their information easily. The output files for the CASC13.txt and CASC14x.txt are available for download at www.inducedseismicity.ca. The CASC is expected to contribute to the study of seismic hazard in Alberta and its surrounding area due to induced seismicity.

There are five original sources for the CASC compilation: the catalog from the TransAlta/Nanometrics (TD) seismographic network (NMX catalog), the Geological Survey of Canada (GSC) catalog (Earthquakes Canada, 2015), the Alberta Geological Survey (AGS) catalog (Stern et al., 2013; Schultz et al., 2015), the Canadian Composite Seismicity Catalog (CCSC) (Fereidoni et al., 2012), and the Advanced National Seismic System (ANSS) comprehensive catalog (NCEDC, 2014). These agencies use information from the following seismic networks (AGS, 2015; Earthquakes Canada, 2015; Eaton, 2014; Stern et al., 2013): the Canadian National Seismograph Network (CNSN), the Alberta Telemetered Seismograph Network (ATSN), the Canadian Rockies and Alberta Network (CRANE), the Montana Regional Seismic Network (MRSN), the United States Reference Network (US-REF), the Regional Alberta Observatory for Earthquake Studies (RV: RAVEN) Network and the TransAlta Dam Monitoring (TD) Network. We assign priority of information from each of these input catalogs based on the network properties and the number of seismic stations used in event locations and magnitudes in the area of study.

2.2 Contributing Agencies and Seismic Network stations

In the past six decades, the seismic networks of Alberta and its surrounding area have gradually improved, with a significant jump in coverage in 2006 and then again in 2013 (Stern et al., 2011, 2013). There are now over 50 stations in Alberta. Here is a brief summary of all the expected seismic network stations contributing to the CASC, which are shown in Figure 2-1. Appendix A is a list of all stations and their dates of operation.

The Geological Survey of Canada (GSC) has monitored earthquakes in Alberta since 1906, with a gradually improving network since the 1960s (Stern et al., 2011 and 2013). The GSC's Canadian National Seismographic Network (CNSN) currently has 19 CNSN stations in and near Alberta (Figure 2-1). Regional CNSN stations also contribute to solutions for larger events. Moreover, many CNSN stations are contributing to the GSC, the NMX, the ANSS and the AGS catalog simultaneously, as other agencies also use this information.

The CRANE stations, located in central Alberta, are semi-permanent non-telemetered seismic stations installed by the University of Alberta since 2006 (Gu et al., 2011). There are 19 CRANE stations (green triangles), as shown in Figure 2-1, though not all are currently operational. The AGS catalog merged the CRANE data with real-time data from CNSC and IRIS (Stern et al., 2013) to improve the accuracy of hypocentres and magnitudes of earthquakes in Alberta for the time period starting in 2006.

The density of seismic stations in Alberta increased further from 2009-2012 when nine broadband seismograph stations were installed by the University of Calgary (Eaton, 2014; Stern et al., 2011 and 2013); these are the ATSN stations (blue circles in Figure 2-1). Some ATSN stations are also affiliated to the Portable Observatories for Lithospheric Analysis and Research Investigation Seismicity (POLARIS) Network (Murphy and Eaton, 2005), and contributed to the GSC catalog. The eight RAVEN (RV) stations (orange plus sign in Figure 2-1) of the AGS are widely used to export waveform data and are shared by different agencies.

Since 2013, Nanometrics Inc. has installed and operated 29 TD stations, shown in Figure 2-2, concentrating in the areas near the Brazeau River, Strachan field, Keep Hills, and areas west of Calgary, on behalf of TransAlta. The aim is to support the induced seismicity hazard (IRC) project in Alberta and monitor seismicity in the vicinity of the TransAlta dams. Nanometrics Inc. maintains an online catalog of events for use by TransAlta and their research partners, including the University of Western Ontario, University of Calgary and the AGS. With the denser network now in place, seismologists are able to better study and identify the characteristics of induced earthquakes.

The AGS, ANSS and NMX catalogs also collect data from a subset of the US-REF stations (grey 4-point stars) operated by the United States Geological Survey (USGS) and a subset of the MRSN stations (pink diamonds) (Figure 2-1). There are three US-REF stations and six MRSN stations routinely used in the AGS and NMX networks.

2.3 Contributing Earthquake Catalogs

The CASC incorporates information from five local, national and international earthquake catalogs: the NMX catalog, the GSC catalog, the AGS catalog, the CCSC catalog and the ANSS catalog. Their properties and contributed time span are different but overlap in some cases, resulting in the need to consider priority of information, conversion of diverse magnitude scales and compilation of alternative locations and magnitudes.

The TD seismic network operated by Nanometrics Inc. (www.nanometrics.ca; last accessed May 2015) began operation in Alberta in August 2013, with 29 seismic stations added over a period of two years. Besides the 29 TD stations, another 25 stations from RV, CNSN, US-REF, ATSN and CRANE networks constitute the complete NMX network (Figure 2-2). The NMX catalog reports the occurrence time, the focal depth, the epicenter in latitude and longitude, the event magnitude, and some comments. In total, 93 events from the NMX catalog are included in the CASC13. Since 2014, the NMX catalog is the primary source of information, but it is only a secondary source in CASC13 as it began operation only near the end of 2013.

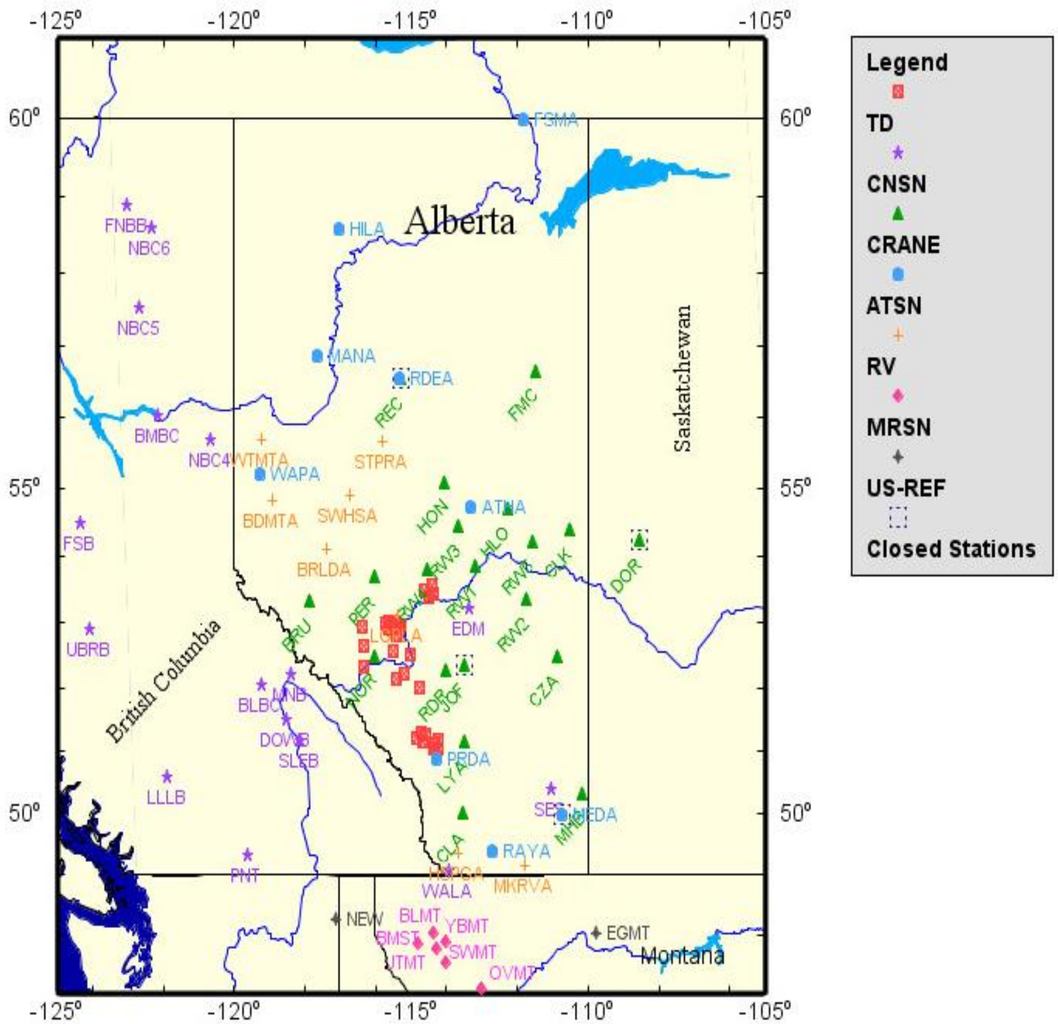

Figure 2-1: Map of Seismic Network Stations employed by different Agencies: 29 TransAlta/Nanometrics seismic network (TD) stations (red squares), 19 Canadian National Seismic Network (CNSN) stations (purple stars), 19 Canadian Rockies and Alberta Network (CRANE) stations (green triangles), nine Alberta Telemetered Seismic Network stations (blue circles), eight Regional Alberta Seismic Network (RV) stations (orange plus signs), six Montana Regional Seismic Network (MRSN) stations (pink diamonds), and three US Array seismic stations (US-REF) (grey 4-point stars). The CNSN stations (YKW3, FCC, and ULM) and the US-REF station DGMT are not shown in this figure. The CNSN station SES, ATSN station MEDA and CRANE stations (JOF, REC and DOR) have been closed (dash-line black square).

GSC's catalog forms the National Earthquake Database (www.earthquakescanada.nrcan.gc.ca/stndon/NEDB-BNDS/bull-eng.php) and contains information for all Canadian earthquakes since 1985. The earthquake parameters arise from the seismograph data recorded by the CNSN and other regional and local cooperating networks. GSC has a backbone network of stations distributed widely in Canada. However, there were less than four seismic stations in Alberta up to 1985, and as of today, only eight CNSN stations in the province. GSC also operates stations in other nearby provinces, which increases the number of effective stations for monitoring the seismicity in Alberta. The current distribution of CNSN seismic stations ensures that all the earthquakes with magnitude greater than 3.5 located in Alberta are detected and recorded in the GSC catalog (Adams and Halchuk, 2003). The GSC catalog includes earthquake date, time (to nearest second in UTC), location, magnitude, depth, a depth designation (whether determined or fixed) and comments. GSC provides the seismicity data prior to 1985 in separate documentations such as the Seismic Hazard Earthquake Epicentre File (SHEEF) (Halchuk, 2009). These additional GSC sources were used by Fereidoni et al. (2012) in the compilation of the Composite Canadian Seismicity Catalog (CCSC), which is described in more detail below.

The CASC contains all the reported events from GSC in the region of 48°- 60° N, 110°-124° W, except for events in the westernmost areas of B.C. (Figure 2-3 and Figure 2-4); it includes all reported event types: earthquakes, induced events, and blasts. It should be noted that the information to designate events as mining-related-events and quarry blasts in the GSC and other catalogs may not be complete. Moreover, not all earthquakes have been categorized as natural or induced. In total, more than 2000 earthquakes and more than 1300 blasts are reported during the period from 1985 to 2013 in the GSC catalog, in the study area. Note that many of these events are located in southwestern B.C. due to the large size included in the study area. The magnitudes of events are mostly reported in the local magnitude scale (*ML*) or Nuttli magnitude (*MN*); a few of the larger events have moment magnitude (**M**) and/or body wave magnitude (m_b) types.

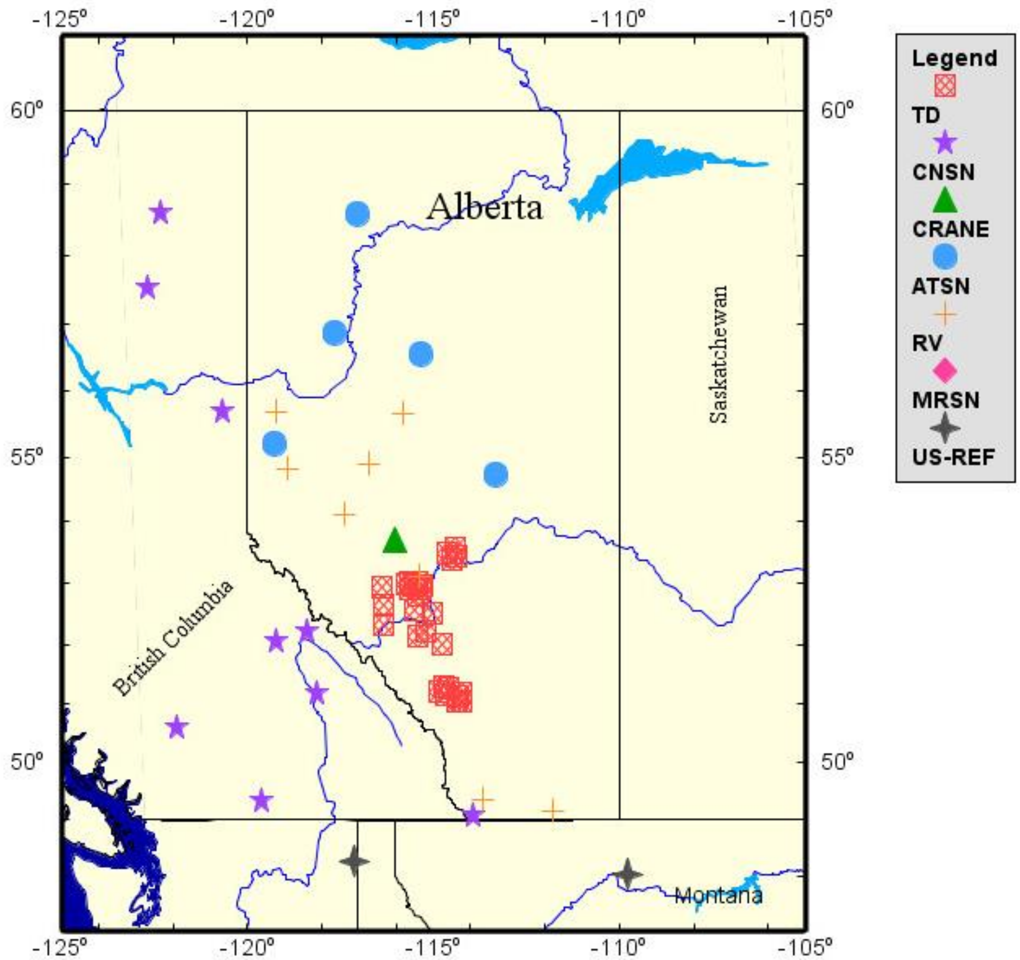

Figure 2-2: Seismic Stations contributing to NMX catalog. 29 TD stations and other 25 stations from CNSN, CRANE, ATSN, RV, and US-REF.

The Alberta Geologic Survey (AGS) Catalog (Stern et al., 2013) is available in the AER/AGS Open File Report 2013-15. The AGS catalog lists the earthquakes in the province of Alberta (or within 10 km of its borders) from September 2006 through December 2010. It differs from the GSC catalog because they included, in addition to CNSN stations, the data from campaign-mode stations, in particular the stations of the Canadian Rockies and Alberta Network (CRANE), which includes several semi-permanent non-telemetered seismic stations by University of Alberta starting in 2006 (Gu et al., 2009). The additional CRANE data enables the detection of more events and improves location accuracy. There are 171 events in the AGS catalog; mining-related-events are removed from the catalog by AGS (thus not included). The depth type includes: ‘g’ when the depth was fixed and ‘f’ when calculated by the location algorithm. The AGS catalog is more complete than the GSC catalog in Alberta, but contains fewer events as it does not go more than 10 km beyond Alberta’s borders.

The CCSC_west Catalog (Fereidoni et al, 2012) is a composite western Canadian Seismicity Catalog compiled by Fereidoni et al (2012) using eight local and international earthquake catalogs. The CCSC contains historical and modern seismicity data to 2013 and is available for download at http://www.seismotoolbox.ca/Catalogs.html. We use the CCSC as the source document for all seismicity data before 1985 in Alberta. In the CCSC catalog, all earthquake duplicates have been removed and different magnitude scales converted to moment magnitude (**M**). The Alberta Composite Catalog is based loosely on the CCSC format. There are 574 events from the CCSC included in the CASC13.

The ANSS comprehensive catalog (http://earthquake.usgs.gov/earthquakes/search/), hosted by the U.S. Geological Survey, provides a beneficial supplement for the CASC, in particular for the southern part of Alberta near the U.S. border . The ANSS comprehensive catalog specifies the type of the events (Earthquake vs Quarry blast) in the catalog.

2.4 Overview of the CASC Catalog

The CASC is a composite earthquake database for the region of 48°- 60° N, 110°- 124° W, excluding the offshore area of BC (Figure 2-3 and Figure 2-4); it includes information of all seismic events located in the province of Alberta and its vicinity. It not only reports date, time, epicentral locations, and depths for the events, but also contains the alternative locations and magnitudes for events that are reported by multiple sources. The CASC contains flags for the original information source and the event type (earthquake vs blast) so that users can manipulate the catalog more easily. The magnitudes of seismic events are homogenized in terms of moment magnitude (**M**) for all reported events, while all original magnitude types, such as *MS*, *ML*, *MN*, *MD*, *MB* and **M** are retained to provide the most complete event characterization. Moreover, the preferred magnitude type is documented based on the information in the primary dataset. Table 2-1 provides the complete list of the parameter entries in the CASC13 and CASCf14x; it should be noted that both datasets are formatted in the same way.

The period of the CASC13 is from 1906 to 2013 and the CASC14x is prepared from the beginning of 2014 up to the last updated date (e.g. June 2015). Figure 2-3 and Figure 2-4 are maps of all the reported seismic events (earthquakes and blasts) in CASC13 and CASC14x, respectively. 4258 events are reported in the CASC13 and 2120 events through June 30th, 2015 in the CASC14x. In the CASC13, more than 2700 events are reported as earthquakes; the others are designated as blasts or mine events. An important note is that not all blasts have been designated in the NMX catalog. The identification of quarry blasts in the NMX catalog is an ongoing task, as discussed by Fereidoni and Atkinson (2015). Figure 2-4 also shows the reported seismicity clusters: clusters of note are those near Fort St. John, Fox Creek, Brazeau River, Rocky Mountain House, Turner Valley and Del Bonita. For example, hundreds of small events between magnitude 1.0 and 4.0 occurred in the Turner Valley cluster from January, 2014 to May, 2015.

2.5 Identifying Duplicates from Catalogs

Because there are multiple sources of information, a challenge in the compilation of a composite catalog is the identification and treatment of duplicates. With the development of seismic instruments and measuring methodologies, and the expansion of networks, the estimation of the earthquake size and location is expected to be more accurate. Hence, the latest NMX catalog should have the highest priority, representing the best information in the CASC comprehensive catalog. The next is the AGS catalog, which uses both GSC stations and the supplementary stations provided by the CRANE, ATSN and US-REF networks. The GSC catalog has the third priority, being based on the national backbone network. The final two catalogs are the ANSS and the CCSC catalogs. If we find an event that appears in multiple catalogs, we report the location, occurrence time and magnitude of the event in the priority catalog as the primary solution, and retain the duplicate solutions in the alternative fields to ensure that the users have access to all the information available (See Table2-1). The alternative locations and magnitudes reported by different agencies are a useful guide for assessment of uncertainties and for the development of conversion relations between magnitude scales.

Handling duplicates is an essential process to generate an accurate composite catalog. After we routinely input all the sources and merged them together chronologically, we identify each set of potential duplicate pairs or triplets. The criteria for identifying duplicates are not entirely straightforward and some manual checking is required. By inspection, we find that almost all the potential duplicates occurred within two seconds in origin time, and are separated by less than 30 km in distance in their locations. Their magnitude difference, however, could be as large as one magnitude unit depending on the reported magnitude scales. Therefore, we use these time, location, and magnitude limits to automatically identify the duplicates in our compilation scripts (e.g. 2s, 30 km, 1**M**). We manually check all events that occur within ten seconds of each other (if also close in space) as there are some time differences between catalogs that exceed two seconds. We also manually check all events within two seconds over a broader space and magnitude window to subjectively identify any duplicates missed in the automatic script criteria. For example, there were seven potential event pairs from AGS and GSC in close proximity in time and space, but having magnitude discrepancy >1 unit. In these cases, the seven events from AGS are considered as duplicates. These duplicates are tabulated in Appendix B.

2.6 Moment Magnitude Conversion

The magnitudes have been reported in various scales including local magnitude (*ML*), surface magnitude (*MS*), duration magnitude (*Md*) and Nuttli magnitude (*MN*). These multiple magnitude types are the results of various measuring methods by different agencies. Moment magnitude (**M**) is preferred for most seismological applications as this magnitude relates well to the total energy released by the earthquake. We therefore convert all event magnitudes to an equivalent moment magnitude value, so that the CASC is homogenous in magnitude type.

Ideally, we should find a series of seismic events with two magnitude types reported, for example *ML* and **M**, to build the relationship between *ML* and **M**. Usually, empirical relations for such conversions can be described by a first order linear equation with slope close to one (Fereidoni et al., 2012). However, in practice, all the events in the contributing catalogs are reported by only one magnitude type, and the use of scales is inconsistent. For this version of CASC13, we used the relationship of magnitude conversion from the CCSC catalog (Fereidoni et al., 2012). Therefore, all the magnitude types are converted to **M** consistently from 1906 to 2013 by the following empirical equations:

$$(1)\ Mb-0.06=\mathbf{M},$$

$$(2)\ MN+0.05=\mathbf{M},$$

$$(3)\ ML+0.12=\mathbf{M}.$$

For CASC14x, the **M** of all events from NMX catalog has been computed using a ground-motion based algorithm (Atkinson, Greig and Yenier, 2014), as described in Novakovic and Atkinson (2015). For the remaining events in CASC14x, empirical relationships are used to convert the instrumental magnitude scales to moment magnitude.

Table 2-1 List of Fields in the Composite Alberta Seismicity Catalog (CASC)

Field No.	Field Names	Comments
1,2,3,4,5,6	[yr mo dy hr min sec]	date and time of earthquake events (UTC)
7,8	[lat lon]	location of earthquake events in latitude and longitude
9,10,11,12,13,14,15	[ML MN MB MW MS MC MD]	different magnitude scale, -9.99 if not available
16	MZ	record events with unknown magnitude type, -9.99 if not available
17,18	[Mpf Tmpf]	preferred magnitude value and preferred magnitude type
19,20,21	[Depth Depth_error dd]	Depth is in kilometer. Depth_error is not available in GSC, CCSC and AGS, documented as -9.99. dd means depth designation.
22	cf	catalog flag: 1=NMX; 2=GSC; 3=AGS; 4=CCSC; 5=ANSS
23	mf	moment magnitude conversion factor (Fereidoni et al., 2012)
24	**M**	Moment magnitude after conversion applied
25	tf	event type: 1= quakes, 2 = blasts, 3 = no information available
26,27,28,29	Alternative location and magnitude from GSC	Latitude, longitude of alternative location in GSC, if available (-9.99 means no alternative location). Magnitude and its type if available.
30,31,32,33	Alternative location and magnitude from ANSS	Latitude, longitude of alternative location in ANSS, if available (-9.99 means no alternative location). Magnitude and its type if available.
34,35,36,37	Alternative location and magnitude from AGS	Latitude, longitude of alternative location in AGS, if available (-9.99 means no alternative location). Magnitude and its type if available.
38	Comments	Any comments provided by original sources.

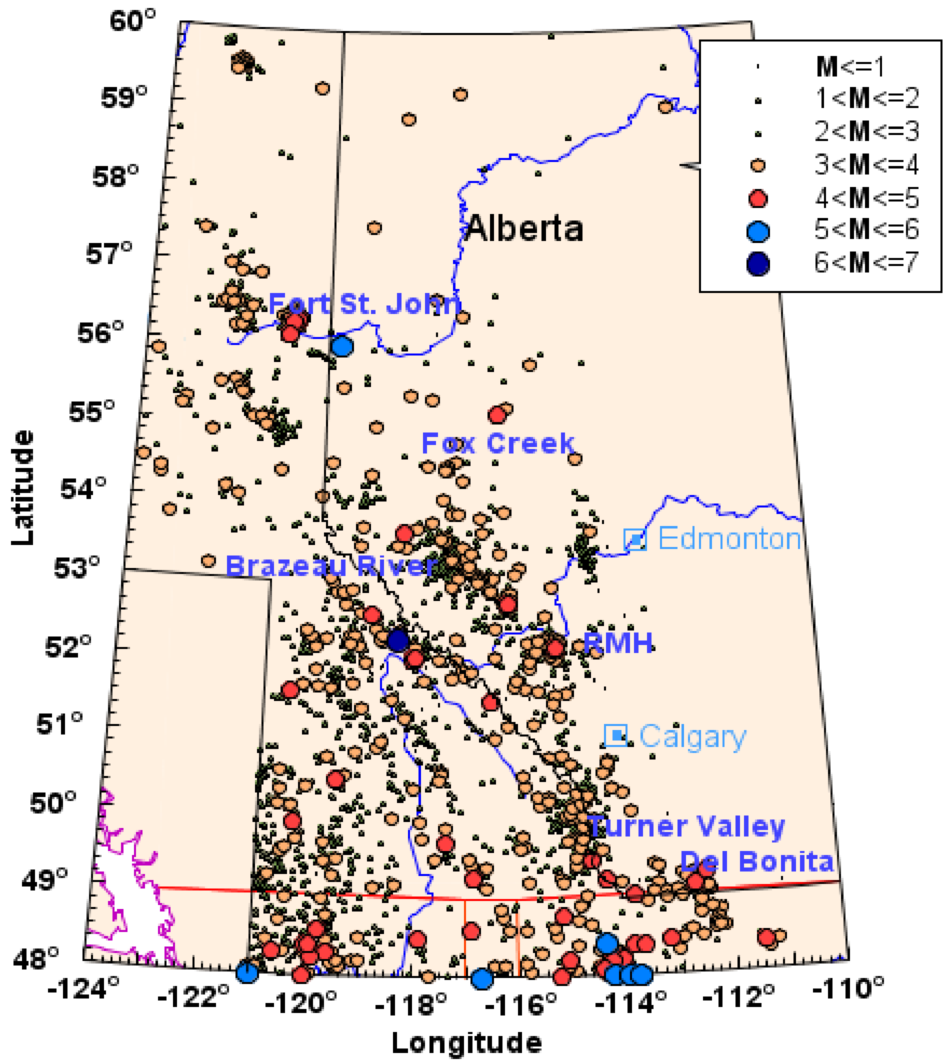

Figure 2-3: Distribution of seismicity in the CASC13 from 1906 to 2013. The colored circles represent magnitude levels. The squares are two major cities. Fort St. John, Fox Creek, Brazeau River, Rocky Mountain House, Turner Valley and Del Bonita are the six main areas of seismicity clusters. RMH means Rocky Mountain House.

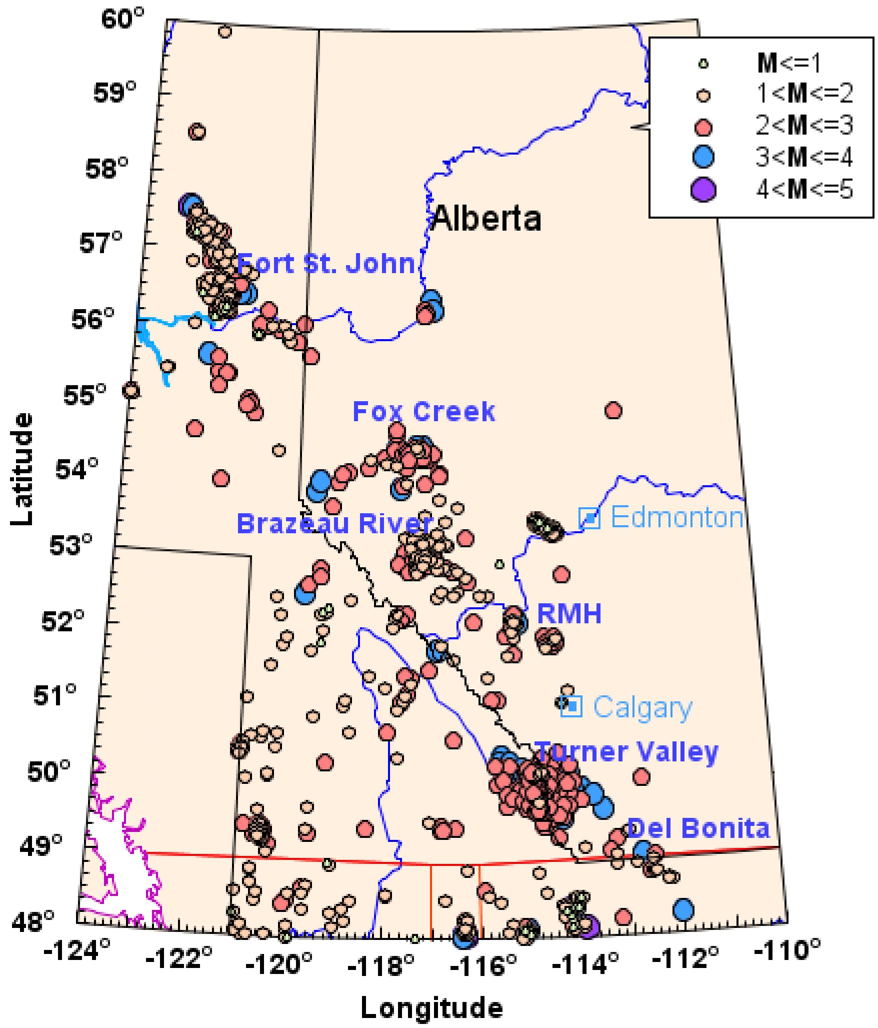

Figure 2-4: Distribution of seismicity in the CASC14x, from January 2014 to May 2015. The colored circles represent magnitude levels. Edmonton and Calgary are two major cities. Fort St. John, Fox Creek, Brazeau River, Rocky Mountain House, Turner Valley and Del Bonita are the six main areas of seismicity clusters.

2.7 Procedures of Data Processing

The compilation of the catalog shown in Figure 2-5 is implemented in a semi-automatic procedure using a computer script written in MATLAB, provided in Appendix C. After obtaining the original source catalogs, we sort event magnitudes into different columns by their corresponding magnitude types and use -9.99 to fill out non-reported values. For each event, we flag it based on its source catalog and event type and calculate the corresponding moment magnitude. Next, we identify duplicate events and document the alternative locations and magnitudes in the alternative fields. The procedure is finalized by generating the two output catalogs: CASC13 and CASC14x. The output format described in Table 2-1 is consistent for the both catalogs; the CASC14x catalog, however, is a living document that is updated monthly. More detailed information on the compilation procedure can be found in the online documentations at www.inducedseismicity.ca. It should be noted that there are many events without magnitude assigned, particularly in the AGS catalog; in these cases, we give priority to the duplicate solutions in other sources. However, a few events without any reported magnitude still exist in the catalog. We retain these events in the final catalog for completeness. Users should pay attention to filter these events if they want to use magnitude information.

2.8 Distinguishing Event Types

In the CASC13 and CASC14x, we flag events types as: 1=quakes and induced quakes; 2= blasts; and 3 =unknown type, where the flags are derived from their original catalog sources. It should be noted that the information about the mining-related-events and blasts may not be complete in the original source catalog. In the NMX catalog, for which the event types are not explicitly identified, we label the events that occurred at a location of known blasting areas during daytime hours as blasts (Fereidoni and Atkinson, 2015). The users should be aware that some events that flagged as earthquakes may have been blasts that were poorly located.

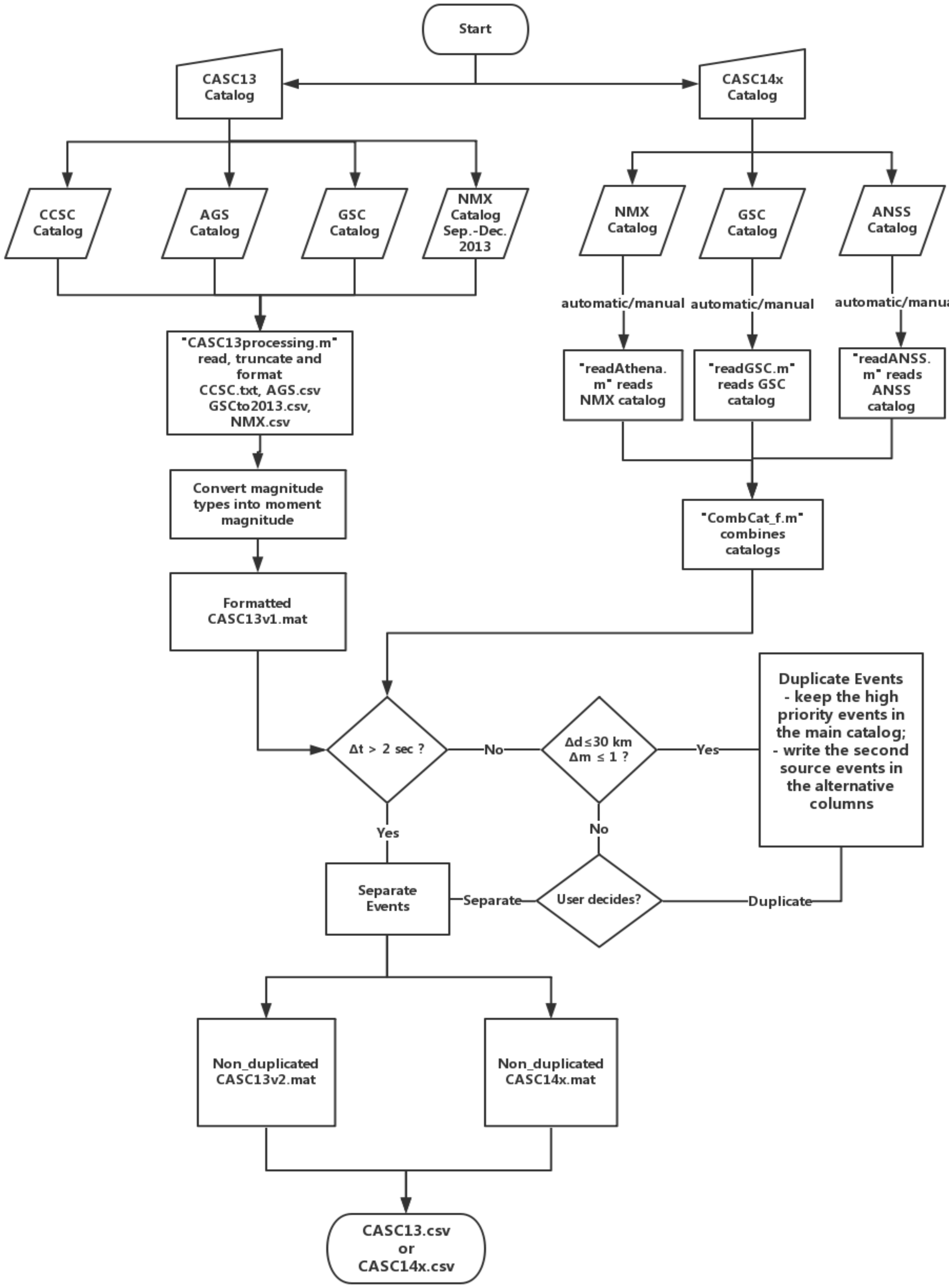

Figure 2-5: Flowchart of the processing procedures.

2.9 Magnitude Completeness in Alberta

The CASC is developed with the aim to provide a comprehensive database of seismicity in and around the province of Alberta from all available sources. The spatiotemporal variations of the magnitude of completeness of the catalog are described in the following chapters. In general, the seismicity of Alberta should be complete above magnitude 3.0 to 3.5 since 1985 (Adams and Halchuk, 2003).

2.10 Summary

The Composite Alberta Seismicity Catalog (CASC) is compiled from multiple sources, with the aim to contribute to the study of induced seismicity hazard assessment in Alberta. It has two subsets: CASC13 covers the period 1906-2013; CASC14x from 2014 to date. These catalogs are available online at www.inducedseismicity.ca along with more detailed documentation. The CASC14x will be updated monthly as agency sources update information products. The CASC is easy to use, modify and manipulate for various seismological purposes. We acknowledge that the CASC may contain incomplete and uncertain information, as do all earthquake catalogs. Users should be aware of these inherent limitations.

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Stern, V. H., Schultz, R. J., Shen, L., Gu, Y. J., & Eaton, D. W. (2013). Alberta Earthquake Catalogue, Version 1.0: September 2006 through December 2010 (pp. 29p): Alberta Energy Regulator.

Chapter 3

3 Overview of Approaches to M_c Estimation

3.1 Introduction

Magnitude of completeness (M_c) is defined as the lowest-magnitude detection threshold at which 100% of earthquakes in that time and space are able to be detected (Rydelek and Sacks, 1989; Wiemer and Wyss, 2000). It is the detection capability of a seismic network, and thus is influenced by the density and distribution of seismic stations, site conditions and data processing capabilities of individual stations (Kvaerna and Ringdal, 1999; Schorlemmer and Woessner, 2008; Mignan and Woessner, 2012). Assessing the completeness of instrumental earthquake catalogs is an essential step for further seismicity analysis. For instance, the Gutenberg-Richter (G-R) relation (equation [3.1]) (Gutenberg and Richter, 1944) is valid above M_c. Knowledge of M_c is crucial for understanding the limitations of an earthquake catalog. For example, an overestimate of M_c leads to under-sampling by removing usable data, while underestimate of it causes biased analysis by using incomplete data.

Multiple methods are available for estimation of M_c. Mignan and Woessner (2012) classify them as catalog-based methods and network-based methods. The catalog-based methods are mostly based on the assumption of self-similarity of the earthquake process (Wiemer and Wyss, 2000; Woessner and Wiemer, 2005; Mignan et al., 2011), implying that M_c is the minimum magnitude at which the observed cumulative frequency magnitude distribution (FMD) departs from the Gutenberg-Richter (G-R) law (equation [3.1]) (Gutenberg and Richter, 1944)

$$log_{10} N = a - b\,(m - M_c), \qquad [3.1]$$

where N is the number of events with magnitude above m, the a-value expresses the earthquake productivity and the b-value controls the relative distribution of small and large earthquakes. Network-based methods use the network distribution to estimate M_c in space based on the proximity to seismic stations (Mignan et al., 2011; Nanjo et al., 2010; Schorlemmer et al., 2010; Plenker et al., 2011). In this chapter, we review the following four representative G-R law-based methods: 1) maximum curvature method (MAXC) (Wiemer and Wyss, 2000), 2) Goodness-of-Fit test (GFT) (Wiemer and Wyss, 2000), 3) M_c for the entire magnitude range (EMR) (Ogata and Katsura, 1993), and 4) M_c by b-value stability (MBS) (Cao and Gao, 2002).

3.2 Maximum Curvature (MAXC) Method

The maximum curvature (MAXC) method (Wyss et al., 1999; Wiemer and Wyss, 2000) defines M_c as the point of the maximum curvature in the cumulative FMD. In practice, it is also the point of the highest frequency in the non-cumulative FMD (Figure3-2). We illustrate the concept for a large region of our study area (see Figure3-1). We downloaded all the 1985 to 2014 earthquakes that occurred in 110° - 121° W longitude, 48°- 60° N latitude from Earthquakes Canada (http://earthquakescanada.nrcan.gc.ca/stndon/NEDB-BNDS/bull-eng.php). Within a magnitude range [0, 6], we count the number of events in 0.1 magnitude intervals and then count the cumulative number of events above each binned magnitude. Then the non-cumulative counts and the cumulative counts are converted to a yearly rateby dividing by the total of 30 years.

Figure 3-2 is the plot of both non-cumulative and cumulative frequency-magnitude relations. The highest point (~2 magnitude) in the non-cumulative FMD does not match the first departure of the observed data (~ 3 magnitude) from the linear trend of the cumulative distribution. There appears to be large uncertainty in M_c, with it lying somewhere in the range from ~2 to ~3.

Although the MAXC method is the fastest and most straightforward technique to estimate M_c, it often underestimates the true M_c in bulk data (Woessner and Wiemer, 2005; Mignan and Woessner, 2012). It is hard to determine the departure point if there is a gradual curvature in the FMD. Moreover, a large number of events (>100) is needed to determine M_c reliably (Wyss et al., 1999), so it is not well-suited to mapping the variations in M_c over a region of sparse seismicity. We also want a map of spatial variation in M_c (x_i, y_i, Δt), so this method is not generally suitable.

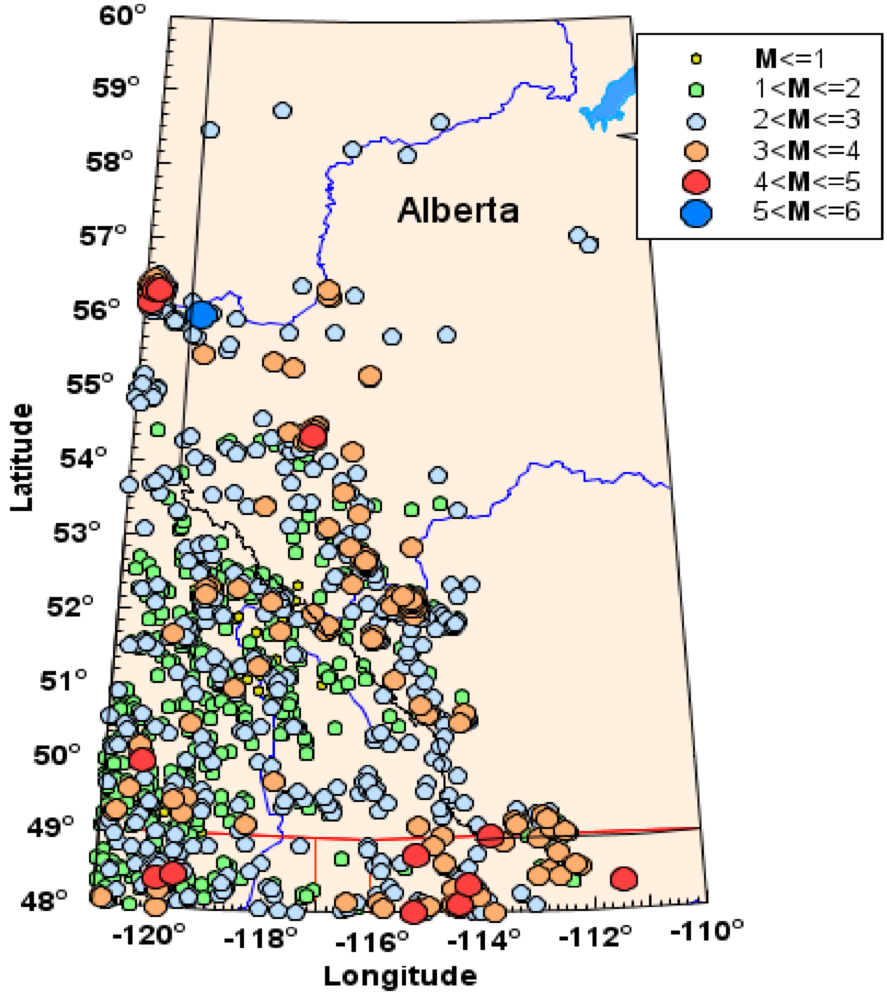

Figure 3-1: Earthquakes during 1985 – 2014 in Alberta and its surrounding area (source: http://earthquakescanada.nrcan.gc.ca/stndon/NEDB-BNDS/bull-eng.php (NRcan, 2015)). The colored circles represent magnitudes.

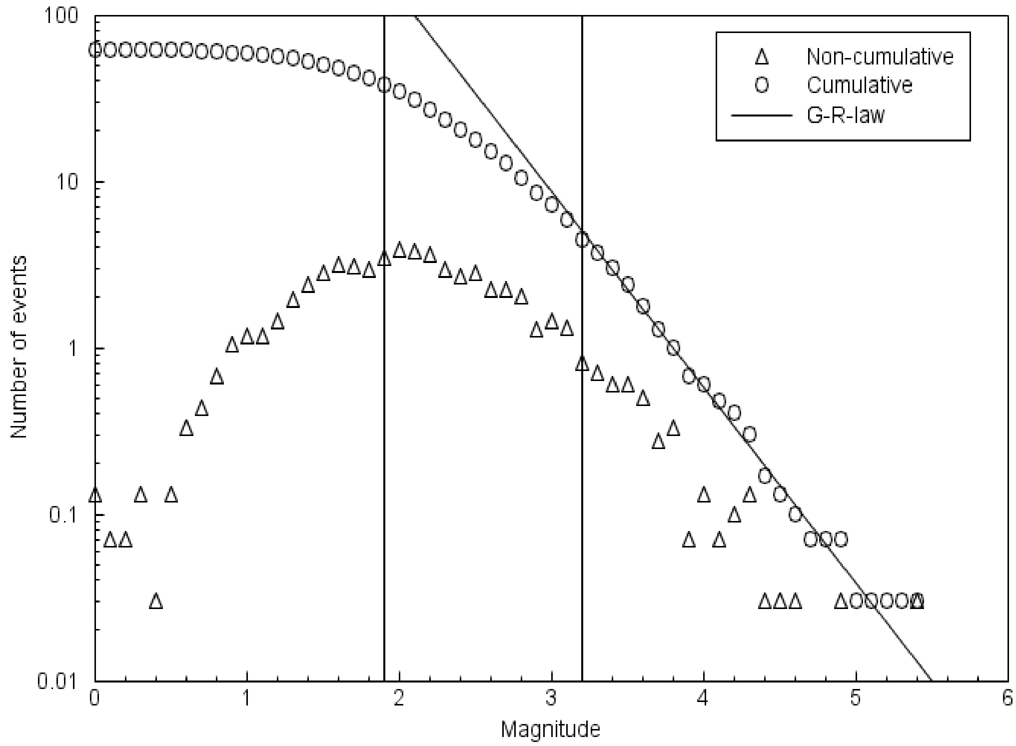

Figure 3-2: Frequency-magnitude distribution (FMD) of the subset of GSC catalog (see Figure3-1). The magnitude types are not homogeneous here, and include local magnitude (ML), Nuttli magnitude (MN) and moment magnitude (M). We assume they are equivalent. The triangles are the non-cumulative counts and the circles are the cumulative frequency. The solid line plots a G-R relation.

3.3 Goodness-of-fit (GFT) Method

As its name implies, the Goodness-of-Fit method (GFT) estimates M_c by finding the departure point *M (i)*, at which a power law can model 90% or more of the data in the frequency magnitude distribution (FMD) (Wiemer and Wyss, 2000). It employss a maximum likelihood method to estimate the *b*- and *a*-values based on assumed minimum magnitudes *M (i)*. Next, one computes synthetic FMDs for each *(b-, a-, M (i)*) combination thatfits a G-R law. Then, the goodness-of-fit R is the absolute difference between the observed and the synthetic sets of the number of events in each magnitude bin. If 90% or more of data ($R \geq 90\%$) can be fitted by the synthetic model, the lower magnitude cut-off *M (i)* is equal to M_c (Figure3-3). However, this method is not adequate for areas of low seismicity such as Alberta due to insufficient data (Wiemer and Wyss, 2000; Woessner and Wiemer, 2005). In addition, although it can map the spatial heterogeneity of M_c, it fails to react to temporal changes due to changes of seismic networks. The seismic network in and around Alberta has been changed several times over the last few decades. Therefore, it is not feasible to apply the GFT method to the study of M_c in Alberta .

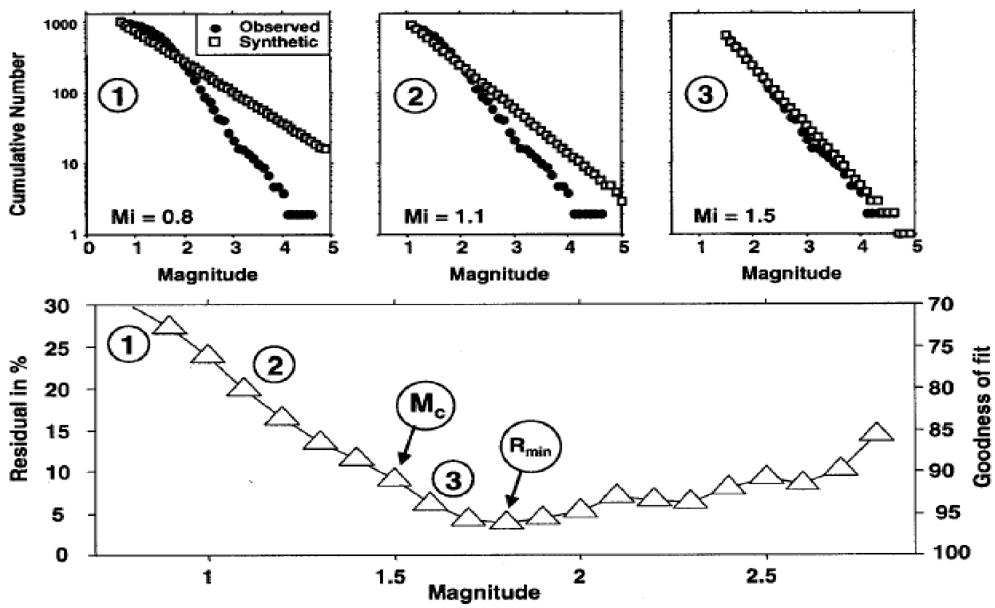

Figure 3-3: Illustration of the GFT method to define magnitude of completeness Mc (Wiemer and Wyss, 2000). With MI approaching to M_c, Goodness of Fit increases.

3.4 The Entire Magnitude Range (EMR) Method

The entire magnitude range (EMR) method separates two parts from the entire FMD relationship: the G-R law for the complete part (magnitude ≥ assumed M_c), and the cumulative normal distribution for the incomplete part of the non-cumulative FMD (Woessner and Wiemer, 2005, Mignan and Woessner, 2012). The idea is derived from

Ogata and Katsura (1993) (hereafter referred to as OK1993), who proposed a probabilistic mechanism of the FMD of detected earthquakes (Figure 3-4). In OK1993, they have postulated that the detection-rate function is the cumulative of the normal distribution, and used maximum likelihood methods to compute M_c. In 2005, Woessner and Wiemer defined this method as the EMR technique. They rewrote the function (equation [3.2]) for the detection probability of a seismic network $q\ (M|\mu,\sigma)$ as:

$$q\ (M|\mu,\sigma) = \begin{cases} \frac{1}{\sigma\sqrt{2\pi}}\int_{-\infty}^{Mc}\exp(-\frac{(M-\mu)^2}{2\sigma^2})dM & , \quad M < Mc \\ 1 & , \quad M \geq Mc \end{cases} \quad [3.2]$$

In equation [3.2], μ denotes the magnitude at which 50% of the earthquakes can be detected and σ indicates the standard deviation. This function shows that, for data above an assumed M_c, the detection probability equals one; for data below the assumed M_c, the normal distribution form fits the observed data. This method needs four parameters to estimate M_c: *a*- and *b*- of the G-R law, as well as μ and σ. The required sample size is greater than 200 events (Woessner and Wiemer, 2005), which renders the method unsuitable for low seismicity areas such as Alberta. The increasing detection capability of the seismic networks with time is another neglected element.

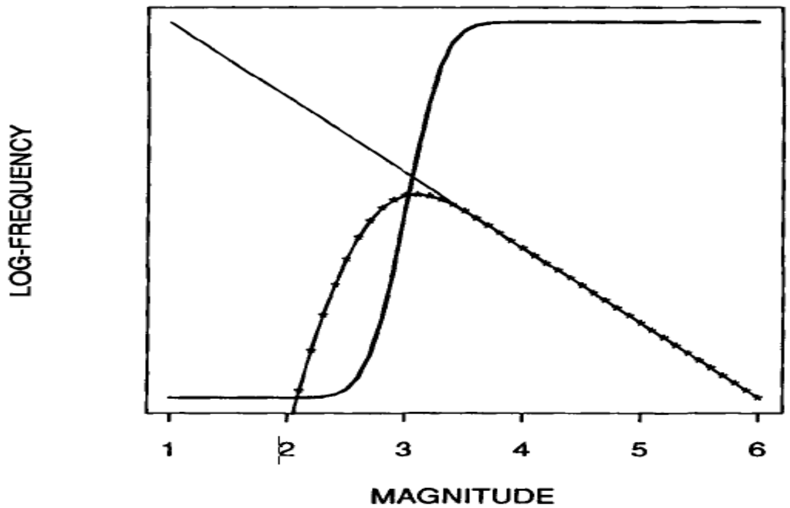

Figure 3-4: Schematic diagram to show the probabilistic mechanism of the FMD of detected earthquakes. The straight line represents the power law in logarithmic scale. The solid thick line with reversed 'z' type indicates the detection-rate probability of events in each magnitude bin in [0.0 1.0]. The dot-line is the non-cumulative FMD (OK1993).

3.5 Method of b-value Stability (MBS)

Using the stability of the *b*-value as a function of cut-off magnitude M_{co} to estimate M_c (Cao and Gao, 2002) is referred to as the MBS method by Woessner and Wiemer (2005).

This method obeys the following conditions:

a) If $M_{co} < M_c$, *b*-value ascends and approaches its true value;

b) If $M_{co} \geq M_c$, *b*-value remains constant;

c) If $M_{co} \gg M_c$, *b*-value ascends again.

This method usually overestimates M_c and has high uncertainties. Woessner and Wiemer (2005) conclude that for mapping purposes, the MBS method is unstable, as the frequency of events in single magnitude bin can be strongly variable.

3.6 Summary

We focus on these four methods (MAXC, GFT, EMR and MBS) because they are the most commonly used methods for estimation of M_c, theoretically similar but with different strengths in application. However, for the reasons provided in the following, we ultimately conclude that GR-based methods will not work well in most parts of Alberta. The seismicity is too sparse, and the M_c is too variable in space and time. In addition, Amorese (2007) proposed the Median-based Analysis of the Segment Slope method to estimate M_c based on an iterative technique to search multiple change points of a non-cumulative FMD. The other catalog-based method is called day-to-night noise modulation (Rydelek and Sacks, 1989), which assumes that the detection threshold due to noise is greater at day but decreases at night because of the cultural activity and wind noise. This method has another assumption, namely that earthquakes follow a Poisson distribution. The advantage of this method is that it does not assume self-similarity of the earthquake process (i.e. the G-R law); however, the catalog used for this method has to be declustered first (Mignan and Woessner, 2012), and would thus not be suitable for application to Alberta, where much of the seismicity of interest is in fact highly clustered.

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Chapter 4

4 Spatiotemporal variations in the Completeness Magnitude of the Composite Alberta Seismicity Catalog (CASC) [2]

4.1 Introduction

Alberta is an area of relatively-low seismic activity (Milne, 1970; Milne et al., 1978; Stern et al., 2013; Schultz et al., 2015a), but there has been growing concern over increasing seismicity levels due to oil and gas activities including hydraulic fracturing operations (BC Oil and Gas Commission, 2012; Atkinson et al., 2015; Eaton et al., 2015; Farahbod et al., 2015; Schultz et al., 2015b), waste water disposal (Horner et al., 1994; Schultz et al., 2014), and gas extraction (Baranova et al., 1999). Over the last decade there has been a significant growth in the seismographic network density (e.g. Stern et al., 2013; Cui et al., 2015), making it difficult to distinguish between rate increases due to oil and gas and rate increases due to improving detection levels. There has also been a proliferation of agencies reporting seismicity (including the Geological Survey of Canada, the Alberta Geological Survey, the U.S. Geological Survey and Nanometrics Inc.). Cui et al. (2015) have compiled all of the contributed public catalogs into a Composite Alberta Seismicity Catalog (CASC), available for download at www.inducedseismicity.ca. This catalog contains all available information on events from these sources, including the alternative estimates of magnitudes and locations. An important aspect of the CASC is that the magnitude of completeness varies greatly in time and space. In this article, we aim to estimate the completeness of the information in the CASC regionally, and map its variability in time and space. This is a challenging exercise because the levels of seismicity are too low in most parts of the study area to

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[2] Cui, L., Atkinson, G.M. (2015). Spatiotemporal variations in the Completeness Magnitude of the Composite Alberta Seismicity Catalog (CASC), manuscript for submission to Seismological Research Letters.

enable statistical methods to be employed. Moreover, the rates of seismicity may be changing in time due to anthropogenic activities. We note that the approach taken here is also applicable to other similar regions (such as the central U.S.) for which we may need to understand the spatiotemporal variation of the magnitude of completeness.

The detection capability of a seismic network depends on many factors, including the station density, the geographic distribution of stations, site conditions, recording characteristics and signal processing methods (Schorlemmer and Woessner, 2008). The magnitude of completeness (M_c) is an oft-cited measure of this capability. M_c is defined as the lowest magnitude, for a specific spatial area during a specific time period, for which one hundred percent of the earthquakes that occurred are detected (Rydelek and Sacks, 1989). In general, the development of seismic networks significantly improves the detection threshold M_c; however, this also means that M_c changes in time and space as new seismic stations are added, complicating its determination. An accurate assessment of M_c is important because underestimation or overestimation of M_c in statistical analysis may lead to biased estimates. In particular, a reliable estimation of M_c is required in order to assess seismicity rate changes, compute magnitude recurrence parameters, and for purposes of earthquake forecasting (Mignan et al., 2011; Mignan and Woessner, 2012). It is because of the importance of M_c that a number of techniques to evaluate or map M_c have been developed.

Mignan and Woessner (2012) provide a comprehensive overview of approaches to M_c estimation, which can in general be classed as catalog-based methods and network-based methods. The catalog-based methods are mostly based on the assumption of self-similarity of the earthquake process (Wiemer and Wyss, 2000; Woessner and Wiemer, 2005; Mignan et al., 2011); specifically, M_c is taken as the minimum magnitude at which the observed cumulative frequency magnitude distribution (FMD) departs from the Gutenberg-Richter (G-R) relation (Gutenberg and Richter, 1944). Network-based methods use the network distribution to estimate M_c based on the proximity to seismic stations (Mignan et al., 2011; Nanjo et al., 2010; Schorlemmer et al., 2010; Plenker et al., 2011). Here we focus on a network-based approach because it is most suitable given the data constraints in this region.

4.2 Methodology for Estimating and Mapping M_c

In this study, we employ a network-based method to map the spatiotemporal variations of M_c in Alberta and its surrounding area. This method is applied to compute the completeness of the CASC catalog from 1985-2015 across a grid of sites covering the study area. The underlying principle is that we expect events to be located and catalogued if they are detected on four or more seismic stations. Thus, we can use the locations and magnitudes of events in the catalog, in combination with the station distribution, to infer the required conditions for detectability, and map their variations in time and space. We model the function $M_c\,(x_i, y_i, \Delta t)$:

$$M_c\,(x_i, y_i, \Delta t) = c_1\, D_4\,(\Delta t) + c_2\,, \qquad [4.1]$$

where $M_c\,(x_i, y_i, \Delta t)$ is the minimum magnitude that can be detected at a node point located in the center of a cell on the grid (at longitude x_i, latitude y_i) in time period Δt, and $D_4\,(\Delta t)$ is the distance from the epicenter of an earthquake to its 4th nearest recording station in the same time period (arc length between the coordinates). Note that c_2 is the distance within which we would require four stations to locate an event of M=0, while c_1 denotes the increase in D_4 per magnitude unit.We determine the coefficients c_1 and c_2 using the CASC catalog (Cui et al., 2015) and a list of stations (including on-off dates) to find what events have been reported in the catalog, at what station distances. We choose the 4th nearest station because network practice in Alberta has been to locate and catalog earthquakes if they were detected on four or more stations. Note that when considered as a prior estimate, the estimate of M_c based on station distribution can be updated in areas where there are sufficient events to make a statistical estimate (about 200; see Mignan et al., 2011).An advantage of the approach is that once the conditions for detectability have been defined in the region, one can map M_c and its uncertainties in both time and space over a grid of sites, including grid points where the seismicity rate may be too low to examine statistically.

Figure 4-1 provides an overview of the station coverage and M>1.5 events in different time periods considered in this study. The time periods of 1985 to 1989 and 1990 to 1999 are merged into one map (Fig.4-1 (a)) due to having only minor changes of stations. When modeling the relation between M_c and D_4, all events reported above zero magnitude are plotted (Fig. 4-2). The stations and their operational dates are summarized from Natural Resources Canada (NRcan) (2015), Stern et al. (2013), and Nanometrics Inc. (2015) in Table 4-1. We compute D_4 (Δt) for every event in the catalog and plot it against magnitude to draw conclusions regarding M_c. We recognize that some temporary stations (such as those deployed for aftershock studies) may not appear in our regional lists and may have increased the magnitude of completeness relative to that mapped here for short periods of time in specific regions. The Rocky Mountain House (RMH) region is a good example of this, as it has been active for decades and hosted several temporary networks that have contributed events to the literature.

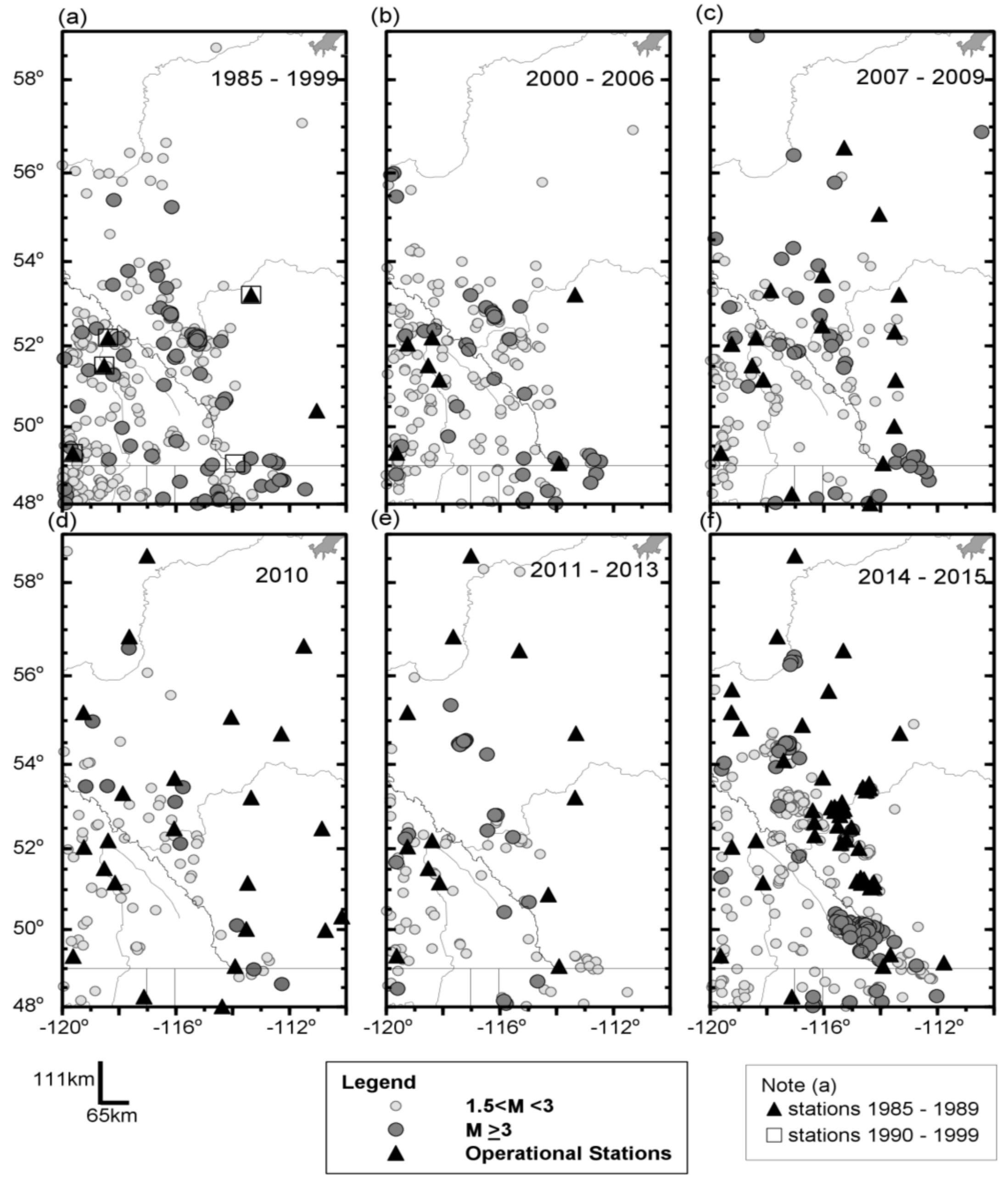

Figure 4-1: Operational seismic stations and earthquake events in different time periods: (a) 1985 – 1989 and 1990 – 1999, (b) 2000 – 2006, (c) 2007 – 2009, (d) 2010, (e) 2011 – 2013, and (f) 2014 – 2015. The black triangles represent operational stations during specific time periods, the circles in various sizes represent earthquake events and their preferred magnitudes. Note that stations beyond the map area are not shown here but listed in Table 4-1.

Table 4-1 Operational Time of Each Seismic Station for the CASC

Time Period	Number of Stations	Added Stations	Shut-down Stations
1985-1989	8	EDM, DOWB, FSB, MNB, PNT, FCC, ULM, and SES (NRCan., 2015)	
1990-1999	9	YKW3 and WALA (NRCan, 2015)	SES
2000-2006	14	SLEB, LLLB, FNBB, BMBC, BLBC (NRCan., 2015)	
2007-2009 (AGS)	36	YKR1,YKR2,YKR4,YKR9, DGMT, EGMT, NEW, YKB3, YKB6, BSMT, JTMT, OVMT, SWMT, YBMT, BLMT, NOR, PER, BRU, CLA, LYA, HON, and DOR (Stern et al., 2013)	
2010 (AGS)	43	CZA, FMC, HLO, MHB, MEDA, WAPA, MANA, and HILA (Stern et al., 2013)	DOR
2011-2013	19* (continuous with time 2000 – 2006)	HILA, MANA, PRDA, WAPA and UBRB (NRCan., 2015)	
2014 - 2015	54	TransAlta/Nanometrics stations and some national stations (TD 001 – TD013, TD022 – TD029, TD016, TD06A, TD07A, TD08A, TD09A, TD13A, TD.CRF, US.EGMT, US.NEW, LGPLA, TD.COP01, Y5.PER, BDMTA, BRLDA, HSPGA, MKRVA, STPRA, SWHSA, WTMTA, ATHA, HILA, RDEA, MANA, WAPA, CN.LLLB, CN.PNT, CN.WALA, CN.MNB, CN.BLBC, CN.SLEB, CN.NBC4, CN.NBC5, CN.NBC6) (NRCan., 2015; Nanometrics Inc., 2015)	

* Note: there are 43 operational stations used by the Alberta Geological Survey (AGS) in this time period, but there is no real-time cataloguing of events; the AGS catalog using these stations is at present complete only to 2010.

4.3 Results

4.3.1 M_c function

To derive a function $M_c = f(D_4)$, we need to consider a catalog dataset for which the underlying seismic network distribution experienced a minimal number of changes; this allows a robust relationship between station locations and catalog events to be defined. For this purpose, we focus on the events contained in the CASC from Aug. 2013 to Jan. 2015, located by Nanometrics Inc. (2015) using a consistent number of stations (Fig. 4-1 (f)). Figure 4-2 shows the computed distance to the 4th nearest station (D_4) for these events, considering their moment magnitudes (**M**) and local magnitudes (*ML*) (see the catalog documentation at www.inducedseismicity.ca (Cui et al., 2015) for information on magnitude determinations and conversions for the CASC); the locations of the events in space is also illustrated. We note that events are spread along the Alberta/B.C. border region, and contain events during both daytime and nightime hours (thus representing both high and low background noise conditions). Events with **M**< 2 are reported as *ML*, and have generally been reported in areas where a number of stations are concentrated, with $D_4 < 25$ km. Larger events (**M** >2) spread from small D_4 (~ 30 km) to large D_4 (~ 300 km) as magnitude increases. From **M** 2.0 to 3.6, there is an obvious trend if we link all the highest points together, which marks the smallest magnitude that can be located for a given value of D_4. If events are smaller than this, the stations are too far apart to provide the required four-station detection.

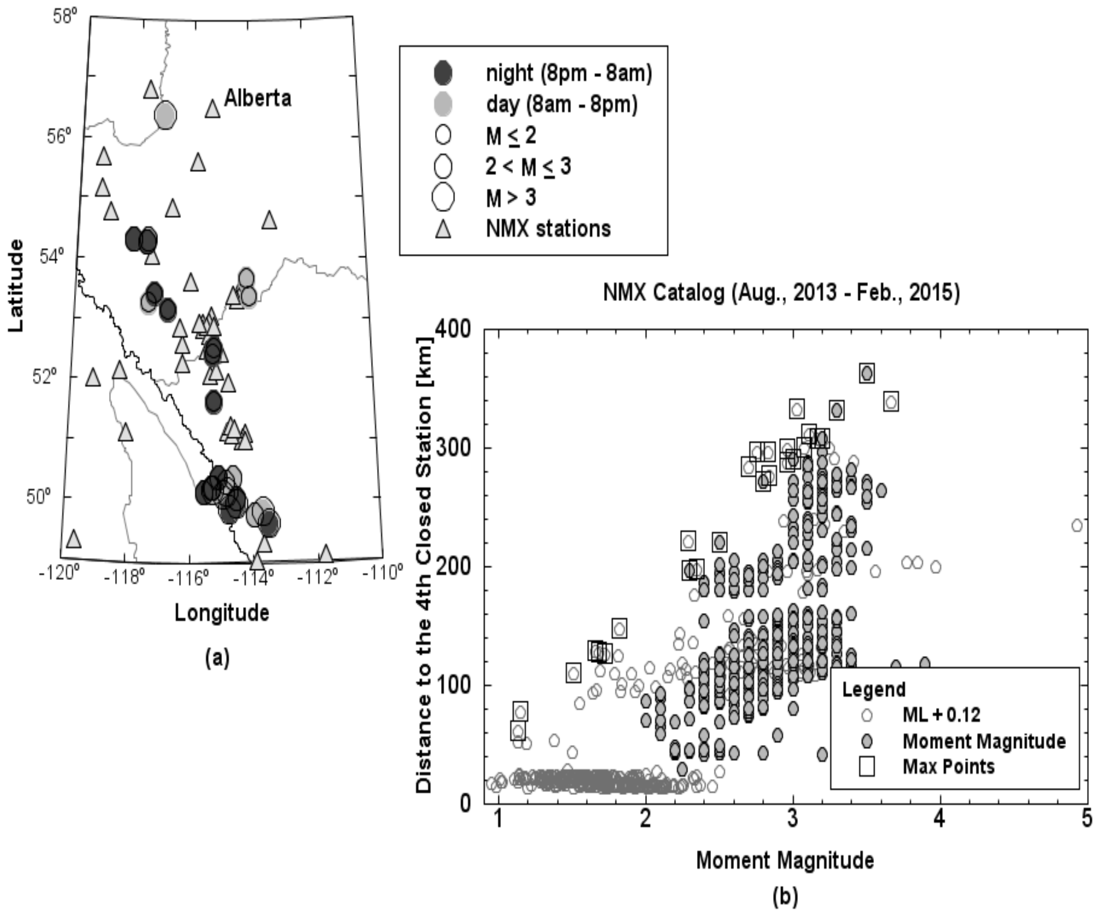

Figure 4-2: Earthquakes in NMX catalog (Aug. 2013-Jan. 2015) used to derive function M_c=*f* (D_4). (a) Map of spatiotemporal distribution of events (squares show events having maximum D4, as highlighted in b. (b) Distance to the 4th nearest station (D_4) versus moment magnitude (M) of NMX catalogue events, with maximum D4 values denoted by squares.

To better describe the D_4 versus **M** variation, Figure 4-3 provides a percentile plot. The lower, inner and upper lines of the boxes are the 25%, 50% and 75% quartiles of the typical distance distribution for the 4th closest station at each magnitude level. It is important to recognize that the points near the upper range of the distribution are not outliers. Rather, these points are highly significant as they characterize the farthest distance that an earthquake in each magnitude level can be detected by at least four seismic stations - though we recognize that in some cases this may also represent ideal observational conditions, such as low noise. The upper ranges of the plotted points form a straight line:

$$D_4 = 132.16 M_c - 82.398 \quad [4.2].$$

The lack of points along this line for intermediate magnitudes may simply indicate of a lack of applicable observations, and might be filled in over a longer time period.

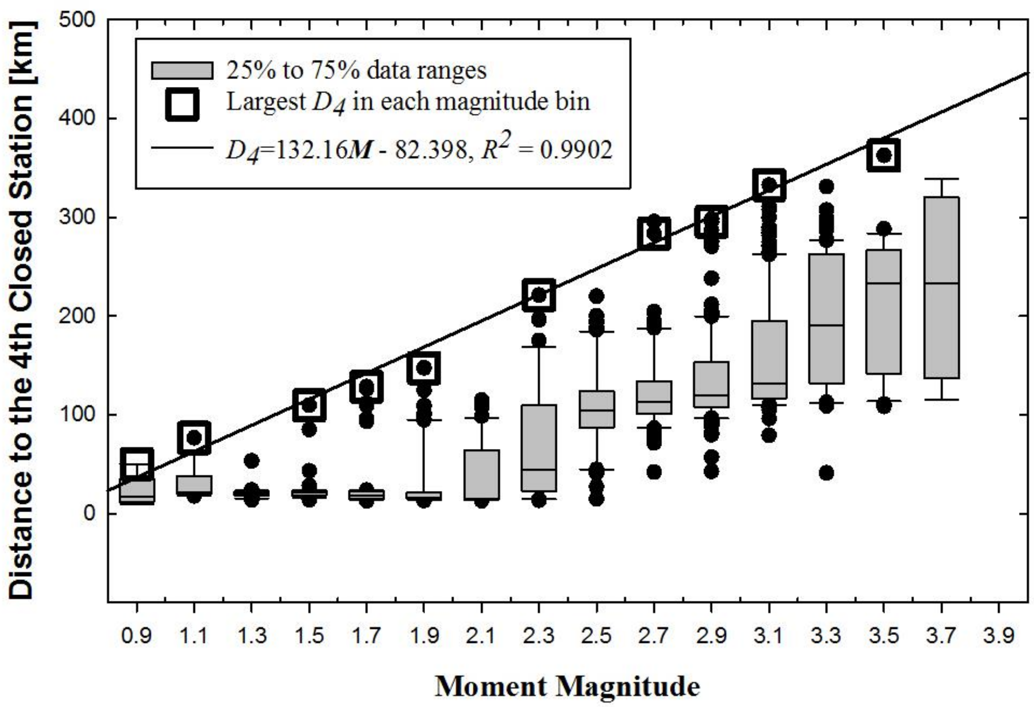

Figure 4-3: Percentile plot for 2013-2015 NMX catalog. The circles represent earthquake events. The lower, inner and upper lines of the boxes represent the 25%, 50% and 75% quartiles of the total number of events in each bin.

We re-arrange Eqn. [4-2] to express the minimum magnitude of events that can be detected by at least four stations:

$$M_c (x_i, y_i, \Delta t) = (D_4 (\Delta t) + 82.398) / 132.16, \quad [4.3]$$

with (x_i, y_i) indicating the longitude and latitude of grid cells, for each of which we calculate D_4 based on the station distribution at time period Δt.

4.3.2 Spatiotemporal Evaluation of Mc in the CASC

We subdivide the CASC into several time periods during which the network configuration was relatively stable (i.e. few changes in stations in Fig.4-1). Until about a decade ago, all the stations were national network stations operated by the Geological Survey of Canada, with stations being gradually added in time (there were only 8 stations in 1985, increasing to 21 stations in 2013) (NRCan, 2015). The Alberta Geological Survey (AGS) and universities in Alberta added stations over the years from 2006-2010 (Stern et al., 2013), then the TransAlta/Nanometrics network added multiple stations in 2013/2014 (Nanometrics Inc., 2015). By looking at the distribution of station additions over time we decided on the following time periods (inclusive): 1985-1989, 1990-1999, 2000-2006, 2007-2009, 2010, 2011-2013, and 2014-2015. We consider the stations which have been operating since the beginning of each time period (and which are generally operational for the entire period) in calculating the M_c values.

We represent the study area by a uniform spatial grid with 110 by 55 center nodes spaced at 0.1° latitude and 0.2° longitude (11 km by 13 km). The value of D_4 at each node is calculated from Eqn. [4.2], using the station configuration for the applicable time period. Eqn. [4.3] is then used to compute M_c values for all nodes. Our method works well in areas of good coverage but is poorly-constrained for areas lacking stations, and as the edges of the map are approached. Hence we need to impose an upper bound on M_c. According to Adams and Halchuk (2003), M_c should not exceed 3.5 in the area of interest in the timeframe of our study, and we therefore impose a maximum value of M_c =3.5. By constraining the maximum value of M_c as equal to 3.5, the largest distance D_4 should be not greater than 380km (Eqn. 4.2). Moreover, since D_4 must be greater than zero, M_c should be not smaller than 0.62 (Eqn. 4.3). In our study, D_4 is always greater than 10km, even for the densest distribution of stations that we have since 2014.Thus, our estimation of M_c should be greater than 0.7. The range of distance D_4 istherefore limited to the range [10km, 380km]. Figure 4-4 maps the spatiotemporal variations of M_c in six contour maps for different time periods: 1985-1989, 1990-1999, 2000-2006, 2007-2009, 2010 and 2011- 2013. Figure 4-5 provides equivalent information for the most recent and complete time period, from mid-2014 to 2015. As the number of seismograph stations increases, smaller M_c values are estimated, especially for the time period 2007 to 2010 with the addition of AGS network stations, and since mid-2014 to 2015 with the addition of the TransAlta/ Nanometrics array.

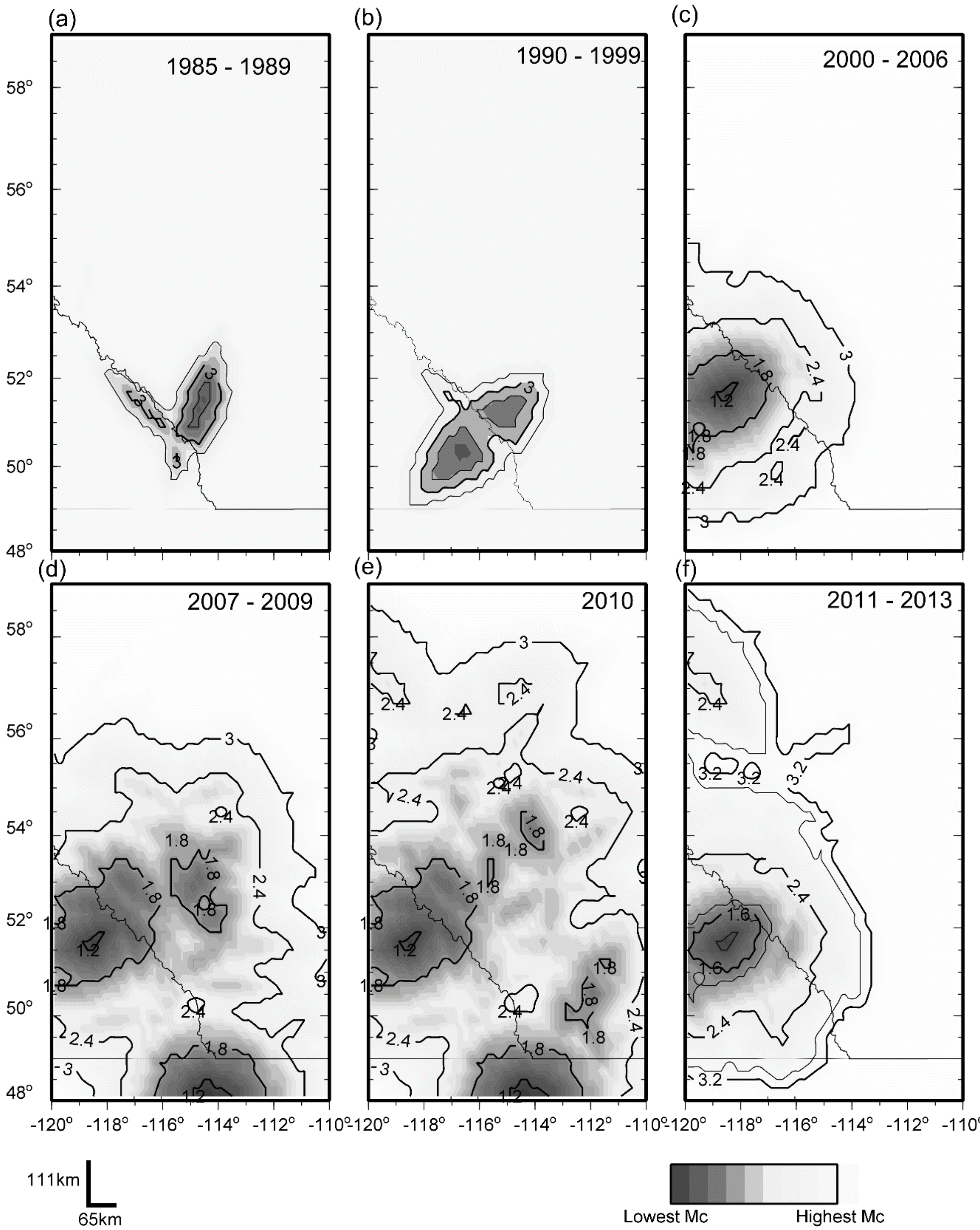

Figure 4-4: Contour maps of estimated M_c for the CASC: (a) 1985-1989; (b) 1990 - 1999; (c) 2000 - 2006; (d) 2007 - 2009; (e) 2010; (f) 2011-2013.

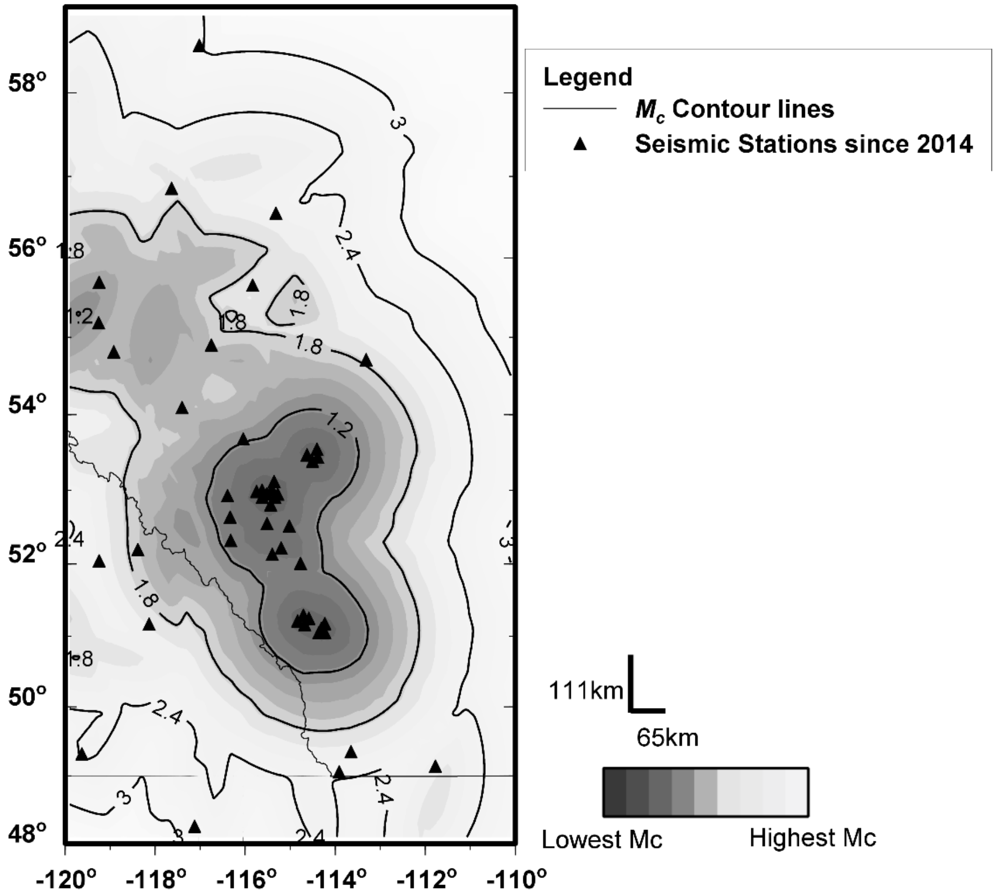

Figure 4-5: Estimated M_c for the CASC for the time period mid-2014 to 2015. The black triangles represent the operating seismic stations.

Note that the minimum value of M_c in the most recent catalogs is <1.0, significantly smaller than the minimum M_c (~ 2.0) available in the catalog provided by the GSC, which does not use all of the stations. Investigating the temporal behavior of M_c for both the AGS and GSC catalogs is useful as the CASC uses both of these sources, and thus the lower of the two M_c values will govern. The recent addition of the TransAlta/Nanometrics stations strongly enhances the detection capability in western Alberta.

4.4 Discussion

4.4.1 Comparison of Results with other Studies

Statistical seismology relies on robust and comprehensive knowledge of the magnitude of completeness of earthquake catalogs and its variability in time and space. This is particularly important for the study of induced seismicity, as we need to be able to distinguish real rate changes from those that may be a consequence of improving station coverage. The method used in this study is advantageous because it is suitable for use with a sparse catalog and a station distribution that changes frequently over time, for which statistical methods are not applicable, and it enables the mapping of M_c in a systematic way in both time and space.

Our method is based on a linear relationship between M_c and D_4 that is derived from the station distribution and catalog observations (Fig. 4-2 & 4-3). Such a relationship has been exhibited in previous studies (Wiemer and Wyss, 2000; Mignan et al., 2011; Schultz et al., 2015a) in slightly-different forms. For example, for a California catalog and an Alaska catalog, Wiemer and Wyss (2000) determined the magnitude of completeness from a study of the statistics of events (Gutenberg-Richter *b*-values across a grid of sites, using 250 events for each *b*-value). They showed that their determined M_c values are closely correlated with the distance to the fourth-closest station. In Figure 4-6, we compare our estimate of M_c based on D_4 with their observations of fitted M_c versus D_4. Wiemer and Wyss use a linear relationship between $log_{10}D_4$ and M_c whereas our observations suggested a simple linear relation between D_4 and M_c. Our relation is very similar to the Wiemer and Wyss relation for Alaska.

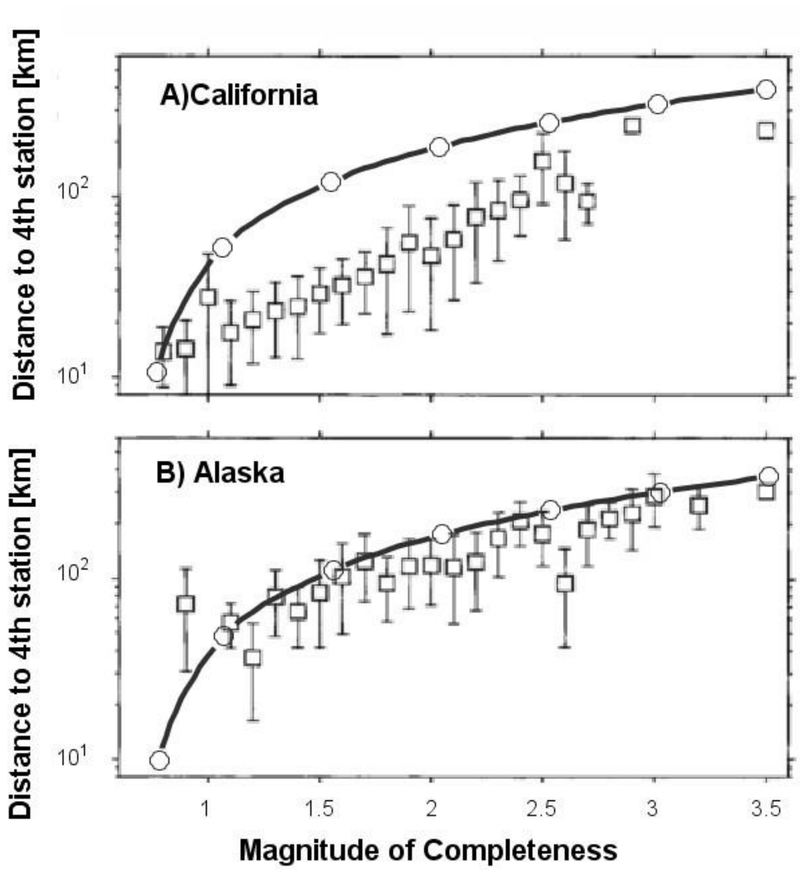

Figure 4-6: Distance to the 4th nearest station as a function of M_c for A) California and B) Alaska (modified from Wiemer and Wyss, 2000), compared to the estimation of M_c for the WCSB from this study, for 2013-2014 (curved lines with circle markers).

In our study, there are no areas with sufficient seismicity to allow meaningful Bayesian updating of M_c based on further statistical analyses, as was performed by Mignan et al. (2011). Similarly, departures from a Gutenberg-Richter relation as employed by Wiemer and Wyss (2000) are not feasible with the sparse seismicity. Moreover, we do not wish to assume stationarity of seismicity or a Gutenberg-Richter relation a priori. Therefore, we have concentrated on use of the catalog to define M_c, assuming that M_c will increase steadily with D_4. This was the rationale for drawing a linear relationship between D_4 and

M_c, though an alternative logarithmic form could also be used, and would provide similar results in the magnitude range of interest (e.g. at $M \geq 2$) .

The results of our method for Alberta may be compared with the results of Schultz et al. (2015a). Schultz et al. (2015a) investigated M_c by combining an analysis of noise levels in waveform data with the simulation of earthquake spectra to quantify station and network performance. They define M_c as the minimum magnitude that should allow for detection and picking of four P phases, which they compute on a grid approximately 5 x 5 km^2 (for a fixed focal depth of 5 km). The M_c of Schultz et al. should be more precise in picking the first four detectable stations and estimating D_4. However, their method is theoretical rather than empirical, and thus the calculated M_c may not always be realized in practice. Moreover, they do not address changes in M_c over time; their study applies to the station distribution used by the AGS as of 2010. We compare our results with those of Schultz et al. (2015a) for 2010 on Figure 4-7. The results are consistent, with both studies suggesting that M_c is close to 2.0 in southern Alberta and increases to 3.0 or above in the north.

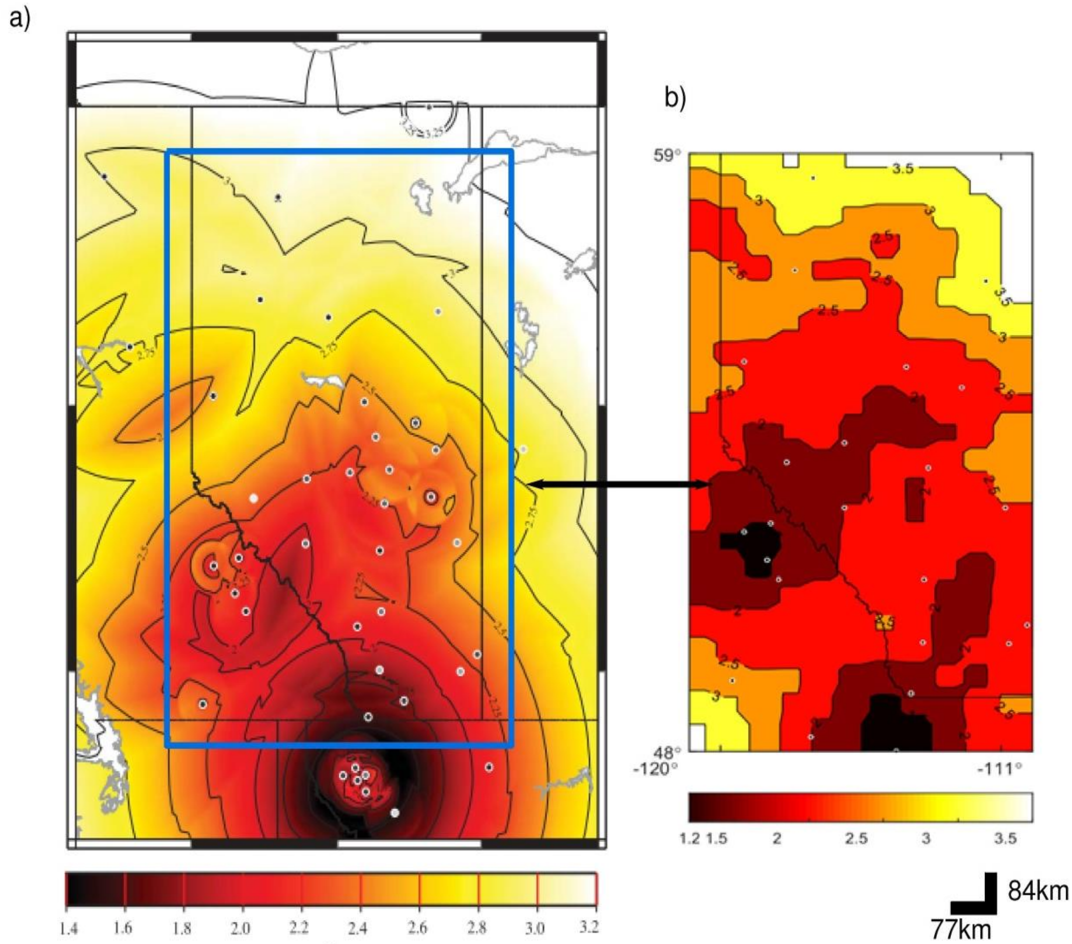

Figure 4-7: Comparison of the estimated magnitude of completeness (*M_c*) in 2010. (Left) based on Schultz et al. (2015a) and (Right) based on our method. The colored contours indicate spatial variations of *M_c*. The dark circles depict seismic stations used for computing *M_c* (left), while the blue rectangle shows our study area (with its *M_c* plotted at right); our study area is smaller than Schultz's mapping area.

4.4.2 Preliminary Statistical Analysis of Seismicity Rates

With completeness thresholds determined since 1985, and magnitudes converted uniformly to moment magnitude **M** in the CASC, average seismicity rates and their variability can now be examined. For this exercise, we use a grid of cells that are 0.5° in latitude and 1° in longitude, as shown in Figure 4-8. The detection threshold M_c for each center node is computed using Eqns. [4.2] and [4.3]. The numbers plotted in Figure 4-8 are simple counts of the total number of events that pass the M_c threshold, from 1985-2013, in each grid of the study area. It also shows the names of the clusters of seismicity for which there are a significant number of events to examine.

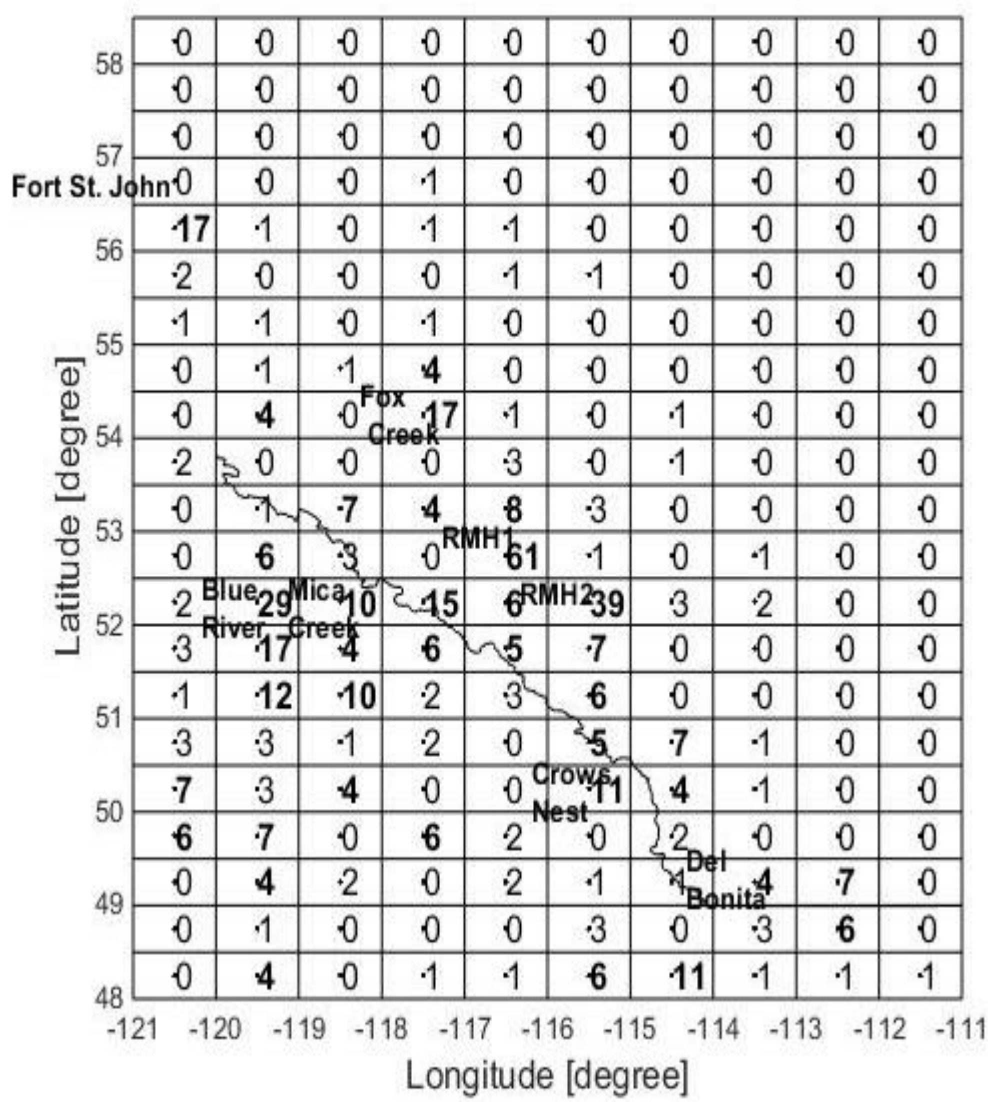

Figure 4-8: Number of earthquakes in the CASC of M ≥M_c from 1985 through 2013 in each grid cell. Eight cells are named by location. RMH stands for Rocky Mountain House.

We use a very simple methodology, based on counting, to take a preliminary look at seismicity rates in the eight named clusters shown in Figure 4-8. To normalize the count to a common basis, as M_c is changing in time and space, we assume that a Gutenberg-Richter relation is applicable, with a nominal *b*-value of 1.0. The assumed value of b is a typical value for this region, as shown by Adams and Halchuk (2003) and Schultz et al. (2015). As a further check on the assumed *b*-value, we compare the observed rates to that for a Gutenberg-Richter relation with *b*=1.0, considering a relatively-active part of the study region, in a time period of relatively-good station coverage. This area, shown in Figure 4-9, has M_c values that range from 1.7 to 2.3 from 2007 to 2010. It is apparent in Figure 4-9 that *b~1.0* for this sample.

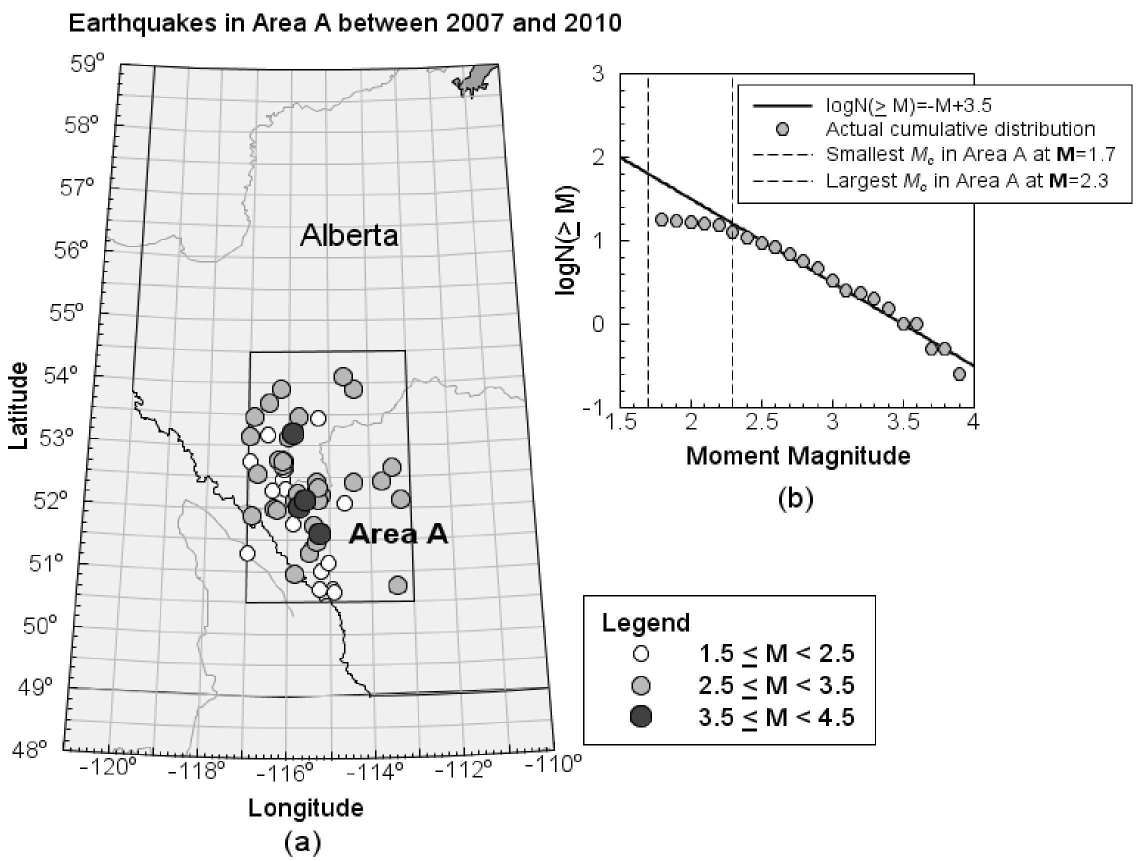

Figure 4-9: Comparison of (a) selected seismicity sample (Area A, 2007-2010) with (b) Gutenburg-Richter relation with *b*=1.0. The dashed lines in (b) represent the range of our M_c estimations for all cells in Area A.

We use the number of events above M_c to compute the equivalent count (in each year, for each cell) that should be obtained for **M** ≥3, assuming *b*=1. We refer to this equivalent rate of events as N_{M3}:

$$N_{M3} = N_{Mc} * 10^{(Mc-3)} \quad [4.4].$$

Figure 4-10 shows the equivalent number of **M** ≥3 earthquakes per year from 1985 to 2014 for the eight cluster areas. Note that in most of these clusters, there have clearly been changes in rate over time, with some areas tending to turn on then off. Areas such as Fox Creek have turned on very recently, due to the recent hydraulic fracturing in that area (Schultz et al., 2015b). Further study of rate changes will be enabled by richer catalogs as additional seismicity continues to be recorded.

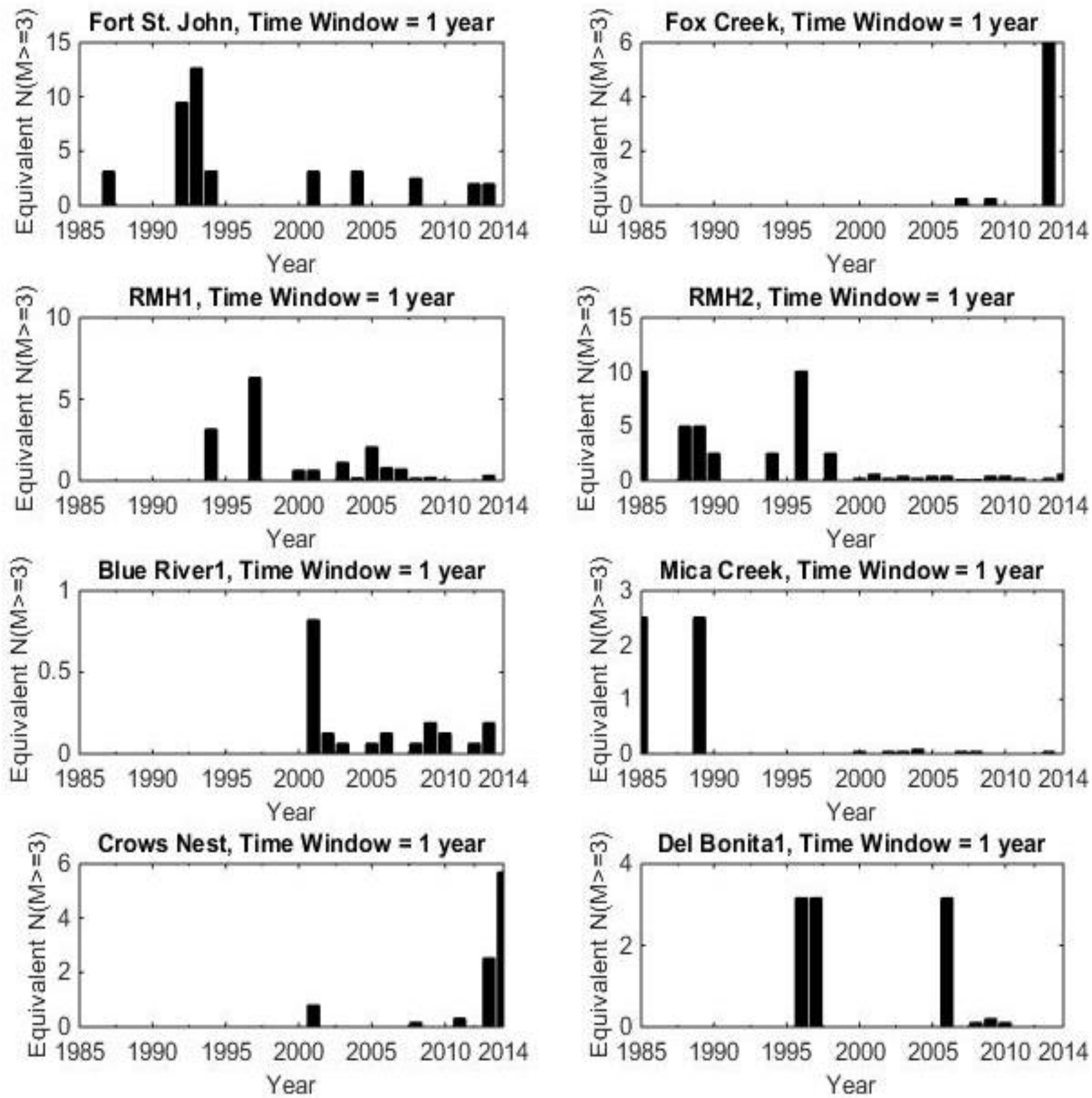

Figure 4-10: Histograms of equivalent number of occurrences of M ≥3 earthquakes per year from 1985 to 2014 for eight clusters identified in Figure 4-8.

4.5 Acknowledgements

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Chapter 5

5 Conclusions and future work

5.1 Summary

Induced earthquakes, those triggered by manmade-activities, have become a pressing and timely problem in Alberta. The aim of this thesis was to do foundational work to assess the problem, such as compilation of various earthquake databases, estimation of magnitude of completeness, and observation of apparent rate changes of seismicity for some seismic clusters.

In Chapter 1, several major reasons for induced seismicity are reviewed: gas and oil production, wastewater disposal and hydraulic fracturing operations (Baranova et al., 1999; BC Oil and Gas Commission, 2012, 2014; Farahbod et al., 2015; Horner et al., 1994; Milne, 1970; Schultz et al., 2014, 2015b). Chapter 2 describes the development of a Composite Alberta Seismicity Catalog (CASC) to provide a useful baseline for studying earthquake hazards due to induced earthquakes in Alberta. The estimation of the completeness of an earthquake catalog is necessary for statistical seismicity analysis. In Chapter 3, various methods to estimate the magnitude of completeness are reviewed. A new catalog-network-based method has been illustrated in Chapter 4. Our method can map the variations of the magnitude of completeness in time and space.

5.2 Results

A prerequisite for many analyses of induced seismicity in Alberta is a comprehensive composite seismicity catalog for Alberta and its surrounding area, allowing characterization of seismicity. Compilation of this catalog, and an estimation of the magnitude of completeness for this catalog and the study area, was the focus of this research. In order to facilitate study of the seismicity induced by hydraulic fracturing and wastewater disposal (Atkinson et al., 2015; Eaton et al., 2015; Farahbod et al., 2015;

Schultz et al., 2014; Schultz et al., 2015a and 2015b), we provide the following valuable products and analysis:

(1) A comprehensive composite seismicity catalog for Alberta and its surrounding area CASC (Cui et al., 2015) is compiled and available for download at www.inducedseismicity.ca, along with its documentation (Chapter 2). It covers the area 48°- 60° N, 110°- 124° W from 1906 to present, combining the information from various earthquake data sources: TransAlta/ Nanometrics Network (NMX catalog), the Geological Survey of Canada (GSC catalog), the Alberta Geological Survey (AGS catalog), the Canadian Composite Seismicity Catalog (CCSC), and the Advanced National Seismic System catalog from the US Geological Survey (ANSS catalog). For each event, the CASC lists the occurrence time in Universal Coordinate Time (UTC), hypocentral location, the set of all available magnitude types, and an assigned preferred magnitude.

(2) A table of spatial magnitude of completeness of the CASC in seven time subdivisions: 1985-1989, 1990-1999, 2000-2006, 2007-2009, 2010, 2011-2013, 2014-2015 based on a longitude of 1° by latitude of 0.5°grid (Appendix E). The estimation method we developed is a catalog-network-based method. We model the relationship between the distribution of seismic stations and the events recorded in the catalog over time, to map M_c (x_i, y_i, Δt) across a grid of the region, where x_i and y_i represent the longitude and latitude of center nodes in the grid and Δt indicates various time periods. The empirical relation determined from the catalog and station data is of the form $M_c(D_4) = (D_4+82.398)/132.16$, where D_4 is the distance from (x_i, y_i) to the fourth nearest station and in the range [10km, 380km]. With this simple relation, it is easy to derive the Mc value for any location in the study area. The script for calculating M_c is available in Appendix D.

(3) A tabulated summary of the entire seismic stations employed by different agencies in the study area (Appendix A), including station names, station locations, on and off dates, status, assigned networks and served catalogs.

(4) A preliminary look at seismicity rate in eight clusters based on simple counting of the total number of events that pass the M_c threshold, from 1985-2013, in each grid cell of the study area. The equivalent number of **M** ≥ 3 earthquakes per year from 1985 to 2014 for the. eight clusters suggest significant changes in seismic rate over time in those areas.

5.3 Future Work

The Composite Alberta Seismicity Catalog (CASC) updates monthly and provides comprehensive information for users. The process of converting various magnitude scales into moment magnitude (**M**) will be improved in future. In addition, the relationship between distance to stations and magnitude of completeness may change its form, as more catalog data become available.

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Appendixes

Appendix A. Station List

Station	Latitude	Longitude	On Date	Off Date	Status	Network	NMXcat	AGScat	GSCcat	ANSScat
PNT	49.32241	-119.62536	1960-01-01		OPEN	CNSN	NMX	AGS	GSC	ANSS
EDM	53.2217	-113.35	1963-04-19		OPEN	CNSN		AGS	GSC	ANSS
FCC	58.7616	-94.0866	1967-06-24		OPEN	CNSN		AGS	GSC	
FSB	54.4767	-124.3283	1979-04-30		OPEN	CNSN		AGS	GSC	
MNB	52.19764	-118.38873	1981-09-29		OPEN	CNSN	NMX	AGS	GSC	ANSS
DOWB	51.518	-118.517	1982-12-01		OPEN	CNSN		AGS	GSC	
ULM	50.250261	-95.874956	1984-09-04		OPEN	CNSN		AGS	GSC	
YKW3	62.49322	-114.60528	1989-01-25		OPEN	CNSN		AGS	GSC	
WALA	49.0595	-113.91116	1992-06-01		OPEN	CNSN	NMX	AGS	GSC	
BSMT	47.8513	-114.787	1995-11-01		OPEN	MRSN		AGS		ANSS
JTMT	47.7467	-114.283	1995-11-01		OPEN	MRSN/MB		AGS		ANSS
OVMT	47.06433	-112.997	1996-10-14		OPEN	MRSN		AGS		
BLBC	52.04401	-119.24386	1997-06-17		OPEN	CNSN	NMX	AGS	GSC	
SLEB	51.1685	-118.1326	1997-12-05		OPEN	CNSN	NMX	AGS	GSC	

BMBC	56.04493	-122.13358	1998-01-30		OPEN	CNSN		AGS	GSC	
LLLB	50.609	-121.8815	1998-11-17		OPEN	CNSN	NMX		GSC	
FNBB	58.89035	-123.00986	1999-10-24		OPEN	CNSN		AGS	GSC	
SWMT	47.5093	-113.999	2001-09-15		OPEN	MRSN		AGS		
YBMT	47.8633	-114.012	2001-09-15		OPEN	MRSN		AGS		
BLMT	48.0108	-114.363	2004-03-11		OPEN	MRSN		AGS		ANSS
JOF	52.34	-113.51	2006-09-18	2007-05-24	CLOSED	CRANE		AGS		
NOR	52.49143	-116.052	2006-09-18		OPEN	CRANE		AGS		
PER	53.68	-116.04	2006-09-28		OPEN	CRANE/Y5	NMX	AGS		
BRU	53.32	-117.87	2006-10-02		OPEN	CRANE		AGS		
CLA	50.01	-113.52	2006-10-02		OPEN	CRANE		AGS		
LYA	51.1551	-113.473	2006-10-02		OPEN	CRANE		AGS		
REC	56.55	-115.28	2006-10-13	2007-06-01	CLOSED	CRANE		AGS		
HON	55.08	-114.05	2006-10-14		OPEN	CRANE		AGS		
CZA	52.49	-110.86	2007-08-31		OPEN	CRANE		AGS		
UBRB	52.89179	-124.08318	2007-10-16		OPEN	CNSN			GSC	
DOR	54.22	-108.57	2007-10-26	2010-04-05	CLOSED	CRANE		AGS		

FMC	56.65	-111.5	2007-11-16		OPEN	CRANE		AGS	
HLO	54.7	-112.28	2009-05-05		OPEN	CRANE		AGS	
MHB	50.32	-110.16	2009-05-10		OPEN	CRANE		AGS	
MEDA	49.98148	-110.742	2009-10-09	2011-08-09	CLOSED	ATSN		AGS	
MANA	56.85538	-117.63672	2009-10-18		OPEN	POLARIS/ RV/ATSN	NMX	AGS	GSC
HILA	58.55608	-117.02029	2009-10-19		OPEN	POLARIS/ RV/ATSN	NMX	AGS	GSC
WAPA	55.18333	-119.25361	2009-10-20		OPEN	POLARIS/ RV/ATSN	NMX	AGS	GSC
PRDA	50.8674	-114.29185	2009-11-13		OPEN	POLARIS/ ATSN		AGS	GSC
RAYA	49.38627	-112.687	2010-08-09		OPEN	ATSN		AGS	
FSMA	59.9862	-111.822	2010-09-12		OPEN	ATSN		AGS	
RW2	53.3493	-111.746	2010-09-17		OPEN	CRANE		AGS	
RW5	54.2043	-111.578	2010-10-01		OPEN	CRANE		AGS	
RW4	53.8006	-114.552	2010-10-13		OPEN	CRANE		AGS	
RW1	53.8529	-113.176	2010-10-15		OPEN	CRANE		AGS	
RW3	54.4415	-113.651	2010-10-15		OPEN	CRANE		AGS	
RDEA	56.55125	-115.3179	2011-06-08		OPEN	POLARIS/ RV/ATSN	NMX	AGS	GSC

RDR	52.2658	-114	2011-09-14	OPEN	CRANE		AGS		
CLK	54.3848	-110.507	2011-09-23	OPEN	CRANE		AGS		
ATHA	54.7137	-113.3137	2012-10-19	OPEN	POLARIS/ RV/ATSN	NMX	AGS	GSC	
TD001	53.54727	-114.40394	2013-01-01	OPEN	TD	NMX			
NBC4	55.68733	-120.66168	2013-03-01	OPEN	CNSN	NMX			
NBC5	57.52314	-122.67767	2013-03-01	OPEN	CNSN	NMX			
NBC6	58.58388	-122.33392	2013-03-01	OPEN	CNSN	NMX			
CRF	45.3428	-75.9007	2013-07-29	OPEN	TD	NMX			ANSS
TD007	52.907	-115.6161	2013-07-31	OPEN	TD	NMX			
TD07A	52.98373	-115.74477	2013-08-01	OPEN	TD	NMX			
TD006	53.00128	-115.62221	2013-08-02	OPEN	TD	NMX			
TD06A	52.94987	-115.52061	2013-08-02	OPEN	TD	NMX			
TD005	53.01361	-115.41135	2013-08-03	OPEN	TD	NMX			
TD08A	52.94756	-115.27764	2013-08-03	OPEN	TD	NMX			
TD09A	52.92497	-116.38973	2013-08-03	OPEN	TD	NMX			
LGPLA	53.11654	-115.35514	2013-10-27	OPEN	RV	NMX			
TD002	53.4394	-114.38764	2013-10-28	OPEN	TD	NMX			
TD004	53.4686	-114.6265	2013-10-30	OPEN	TD	NMX			

TD003	53.38668	-114.50594	2013-10-31	OPEN	TD	NMX
COP01	52.9039	-115.3398	2013-11-01	OPEN	TD	NMX
TD008	52.80409	-115.43176	2013-12-13	OPEN	TD	NMX
TD13A	52.00769	-114.76824	2013-12-19	OPEN	TD	NMX
TD009	52.32058	-116.32337	2013-12-22	OPEN	TD	NMX
TD010	52.63863	-116.33301	2013-12-22	OPEN	TD	NMX
TD011	52.54942	-115.5157	2013-12-23	OPEN	TD	NMX
TD013	52.51791	-115.02345	2013-12-23	OPEN	TD	NMX
TD012	52.13135	-115.39685	2014-01-17	OPEN	TD	NMX
TD024	51.04789	-114.36208	2014-05-04	OPEN	TD	NMX
TD023	51.11063	-114.30516	2014-05-05	OPEN	TD	NMX
TD025	51.16141	-114.67631	2014-05-05	OPEN	TD	NMX
TD027	51.05079	-114.23182	2014-07-06	OPEN	TD	NMX
TD022	51.17701	-114.2288	2014-07-07	OPEN	TD	NMX
TD026	51.29277	-114.70697	2014-07-08	OPEN	TD	NMX
BDMTA	54.81291	-118.9149	2014-08-15	OPEN	RV	NMX
BRLDA	54.09199	-117.40384	2014-08-15	OPEN	RV	NMX
HSPGA	49.3527	-113.65233	2014-08-15	OPEN	RV	NMX
MKRVA	49.143	-111.77547	2014-08-15	OPEN	RV	NMX

STPRA	55.66063	-115.83232	2014-08-15		OPEN	RV	NMX			
SWHSA	54.89944	-116.75179	2014-08-15		OPEN	RV	NMX			
WTMTA	55.69422	-119.23975	2014-08-15		OPEN	RV	NMX			
TD029	52.21709	-115.20005	2014-10-23		OPEN	TD	NMX			
TD016	51.21033	-114.83547	2014-10-24		OPEN	TD	NMX			
TD028	51.24942	-114.58781	2014-10-24		OPEN	TD	NMX			
SES	50.396	-111.042	1966-00-00	1993-03-31	Closed	CNSN		AGS	GSC	
DGMT	48.47	-104.196	1972-00-00		OPEN	US-REF		AGS		
EGMT	48.024	-109.755	1972-00-00		OPEN	US-REF	NMX	AGS		
NEW	48.263	-117.12	1972-00-00		OPEN	US-REF	NMX	AGS		ANSS

Appendix B. Duplicates from AGS catalog

year	month	day	hour	minute	second	latitude	longitude	ML	Depth	dd	mf	Mw_Rev	tf	comments
2006	10	21	6	51	56	52.717	-116.120	0.51	1	'f'	0.12	0.63	1	'26 km NNW of Harlech '
2006	10	21	9	26	55	52.676	-116.150	0.41	6	'f'	0.12	0.53	1	'23 km NW of Harlech '
2006	12	5	8	0	34	52.689	-115.960	0.77	1	'g'	0.12	0.89	1	'21 km N of Harlech '
2007	2	26	15	14	60	52.618	-116.100	0.58	2	'f'	0.12	0.7	1	'15 km NW of Harlech '
2007	10	16	11	33	47	52.714	-116.150	0.80	3	'f'	0.12	0.92	1	'26 km NW of Harlech '
2007	11	23	12	48	36	52.721	-116.170	0.61	1	'g'	0.12	0.73	1	'27 km NNW of Harlech '
2008	3	23	7	57	48	52.667	-116.110	0.52	1	'g'	0.12	0.64	1	'19 km NNW of Harlech '

Note: Additional events in AGS Catalog that we assume are duplicates; the GSC ML values have been preferred for these events.

Appendix C. Matlab Script for the semi-automated processing of CASC 2013

```
% Input earthquake catalogs:

% 1) GSC.csv - Earthquake Canada download (1985 year to 2013-12-31)

% 2) AGSformatted.csv - includes Alberta earthquake data from 2006 to
2010 year (Stern, 2010)

% 3) CCSC11west.txt - (Fereidoni et al., 2012)



%%%%%processing ccsc11west.txt%%%%%%%

%truncate data in time window 1906-1984end, after 1984, GSC data started
to

%apply.

%truncate data in Alberta area polygon latitude between 48degree to

%59degree north, -110~-121 degree in longitude



% Output earthquake catalog:



% The Composite Alberta Seismicity Catalog2013.csv(CASC13 earthquake

% catalog)

% this catalog has been sorted by time but includes duplicates which

% will be verified and removed lately in excel manually.



%CASC13 format:

%We want to keep the same format with CCSC (A composite Canadian

%seismicity catalog) so that it is easier to compare with each other in
future.



% [year month day hour minute second latitude longitude ML MN MB MW MS
MC MD MZ Mpf Tmpf Depth Dth_or dd cf zf mf Mw_Rev tf comments].
```

```
%var        col           Name [unit]
%yr          1              year
%mo          2              month
%dy          3              day
%hr          4              hour
%min         5              minute
%sec         6              second
%lat         7              latitude
%lon         8              longitude
%ML          9              local magnitude
%MN         10              Nuttli magnitude
%MB         11              body wave magnitude
%MW         12              moment magnitude
%MS         13              surface wave magnitude
%MC         14              coda magnitude
%MD         15              Duration magnitude
%MZ         16              unknwon magnitude type
%Mpf        17              preferred magnitude
%Tmpf       18              type of the preferred magnitude
%Depth      19              depth
%Dth_or     20              depth error
%dd         21              depth designation
%cf         22              Catalogue flag (1:GSC 2:AGS 3:CCSC)
%zf         23              Seismic source zone flag (unavailable for
%now,keep zero)
%mf         24              Mw additive conversion factor
%Mw_Rev     25              Updated moment magnitude
```

```
%tf         26                event type:  1=earthquake 2=blast 3=not
%avaliable
%comments   27                statements of regions, locations or comments
clear all
clc
disp('                                                         ');
disp('-----   Compilation of CASC13 earthquake catalog   -----');
disp('Current path
is:C:\Users\luqi\Documents\MATLAB\CASC13\newboundaryCASC2');


%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%Section1:CCSC_west_data_processing%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
disp('section1: processing ccsc_west_data');


%%%%%%read ccsc11west.txt%%%%%
%ccsc11wesst catalog includes all the data in West Canada from 1906 to
%2010, first step should be to truncate ccsc_west into specific time
window
%and location window; because after 1985, Earthquake Canada started to
have more
%accurate data for Alberta area, we will only choose data of ccsc_west
from 1906 to 1984


[yr1,mo1,dy1,hr1,min1,lat1,lon1,Mb1,MN1,Ml1,Ms1,Mc1,Md1,Mw1,Mm1,Mz1,Mpf1
,Tm1,Depth1,dd1,~,~,mf1,new_Mw1] = ...

textread('C:\Users\luqi\Documents\MATLAB\CASC13\newboundaryCASC2\ccsc11w
est.txt',...
```

```
'%4d %02d %02d %02d %02d  %7.3f  %9.3f  %5.2f %5.2f %5.2f %5.2f %5.2f %5
.2f %5.2f %5.2f %5.2f %5.2f %s  %06.2f %s  %1d  %3d  %5.2f  %5.2f','head
erlines',50);


%%%%%%specify time window%%%%%

ts=1905;

te=1985;

itw=(yr1>ts)&(yr1<te);


%%%%%%specify polygon region in the vectors xv and yv%%%%%


xv = [-121 -121 -124 -124 -110 -110]'; % longitude of Alberta area

yv = [48 53 53 60 60 48]';% latitude of Alberta area


x=lon1; y=lat1;

xv=[xv;xv(1)]; yv=[yv;yv(1)];

in=inpolygon(x,y,xv,yv);


yr  = yr1(in&itw);   mo = mo1(in&itw);  dy = dy1(in&itw);

hr  = hr1(in&itw);   min = min1(in&itw);

lat = lat1(in&itw); lon = lon1(in&itw);

ML=Ml1(in&itw); MN=MN1(in&itw); MB=Mb1(in&itw);

MW=Mw1(in&itw); MS=Ms1(in&itw); MC=Mc1(in&itw); MD=Md1(in&itw);

MZ=Mz1(in&itw); Mm=Mm1(in&itw); Mpf=Mpf1(in&itw); Tmpf=Tm1(in&itw);
Depth=Depth1(in&itw);

dd=dd1(in&itw); mf=mf1(in&itw); Mw=new_Mw1(in&itw);
```

```
clear yr1 mo1 dy1 hr1 min1 lat1 lon1 Ml1 MN1 Mb1 Mw1 Ms1 Mc1 Md1 Mz1 Mm1
Mpf1 Tm1 Depth1 dd1 mf1 new_Mw1 x y xv yv te ts itw;


%%%%%write ccsc_Alberta catalog%%%%%

sec=zeros(length(yr),1);

cf=4*ones(length(yr),1);

Dth_or=zeros(length(yr),1);

%zf=zeros(length(yr),1);

tf=3*ones(length(yr),1);

comments=cell(length(yr),1);


disp('generate dataset data_ccsc');

data_ccsc11=dataset(yr,mo,dy,hr,min,sec,lat,lon,ML,MN,MB,MW,MS,MC,MD,MZ,
Mpf,Tmpf,Depth,Dth_or,dd,cf,mf,Mw,tf,comments);


clear yr mo dy hr min sec lat lon ML MN MB Mw Ms Mc Md Mz Mpf Tmpf Depth
Dth_or dd mf Mnew Mm in MC MD MS MW MZ tf;

clear comments cf;

export(data_ccsc11,'file','ccsc11.csv','Delimiter',',');




%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%Section2:GSC_data_processing%%%%%%%%%%%%%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%


%%%%%read GSC catalog%%%%%

fid=fopen('C:\Users\luqi\Documents\MATLAB\CASC13\newboundaryCASC2\GSC198
5to2010newboundaryformatlab.csv');
```

```
%depth is numberwith 'g', for example 1.0g or 1.0*. Here, we exclude
'g'or

%'*'from the original data to generate the new catalog

format='%4d %02d %02d %02d %02d %02d %f %f %f %s %f %2s %d %s %*[^\n]';


data=textscan(fid,format,'delimiter',{',','/',':'},'headerlines',1);

fclose(fid)


%%%%%process GSC data%%%%%

yr1=cell2mat(data(1));

mo1=cell2mat(data(2));

dy1=cell2mat(data(3));

hr1=cell2mat(data(4));

min1=cell2mat(data(5));

sec1=cell2mat(data(6));

lat1=cell2mat(data(7));

lon1=cell2mat(data(8));

mag1=cell2mat(data(11));

magt1=data{1,12};

Depth1=cell2mat(data(9));

dd1=data{1,10};

tf1=cell2mat(data(13));

comments1=data{1,14};

%%%%%%specify polygon region in the vectors xv and yv%%%%%

%2866 out of9808 left

xv = [-121 -121 -124 -124 -110 -110]'; % longitude of Alberta area

yv = [48 53 53 60 60 48]';% latitude of Alberta area
```

```
x=lon1; y=lat1;
xv=[xv;xv(1)]; yv=[yv;yv(1)];
in=inpolygon(x,y,xv,yv);
yr  = yr1(in);   mo = mo1(in);  dy = dy1(in);
hr  = hr1(in);   min = min1(in); sec=sec1(in);
lat = lat1(in); lon = lon1(in);
Depth=Depth1(in);
dd=dd1(in);
mag=mag1(in);
magt=magt1(in);
tf=tf1(in);
comments=comments1(in);
%%%%%%specify time window%%%%%
ts=2006;
itw=yr<ts;
%%%%%remove previous region%%%%%
%2416 out of 2866
xv1 = [-121 -121 -110 -110]'; % longitude of Alberta area
yv1 = [48 59 59 48]';% latitude of Alberta area
xv1=[xv1;xv1(1)]; yv1=[yv1;yv1(1)];
in1=inpolygon(lon,lat,xv1,yv1);
in1=~in1;
yr  = yr(itw|in1);   mo = mo(itw|in1);  dy = dy(itw|in1);
hr  = hr(itw|in1);   min = min(itw|in1); sec=sec(itw|in1);
lat = lat(itw|in1); lon = lon(itw|in1);
Depth=Depth(itw|in1);
dd=dd(itw|in1);
```

```
mag=mag(itw|in1);

magt=magt(itw|in1);

tf=tf(itw|in1);

comments=comments(itw|in1);

[ML MN MB MW MS MC MD MZ Mpf Tmpf mf Mw] = compare_magt(mag,magt);

Dth_or=zeros(length(yr),1);

cf=2.0*ones(length(yr),1);

disp('generate dataset data_GSC');

data_GSC=dataset(yr,mo,dy,hr,min,sec,lat,lon,ML,MN,MB,MW,MS,MC,MD,MZ,Mpf
,Tmpf,Depth,Dth_or,dd,cf,mf,Mw,tf,comments);

clear dd dy hr j lat location lon Depth Dth_or MB ML MN MC MD Mw Mpf MS
MW MZ Tmpf mag magt mf min mo sec zf time_array yr;

clear tf comments fid format cf ;

clear data format ;

clear ans comments1 dd1 Depth1 dy1 hr1 in in1 itw lat1 lon1 mag1 magt1
min1 mo1 sec1 tf1 ts x xv xv1 y yr1 yv yv1

export(data_GSC,'file','GSC1985to2010.csv','Delimiter',',');

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%%%%%%%%%%updated_CCSC13westEq%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%


format='%4d %02d %02d %02d %02d  %7.3f  %9.3f  %5.2f %5.2f %5.2f %5.2f %
5.2f %5.2f %5.2f %5.2f %5.2f %5.2f %s  %06.2f %s  %1d  %3d  %5.2f  %5.2f
';

[yr1,mo1,dy1,hr1,min1,lat1,lon1,Mb1,MN1,Ml1,Ms1,Mc1,Md1,Mw1,Mm1,Mz1,Mpf1
,Tm1,Depth1,dd1,cf1,~,mf1,new_Mw1]=...


textread('C:\Users\luqi\Documents\MATLAB\CASC13\newboundaryCASC2\CCSC201
3_west_earthquake.txt',format,'headerlines',3);

%%%%%%specify polygon region in the vectors xv and yv%%%%%

xv = [-121 -121 -124 -124 -110 -110]'; % longitude of Alberta area

yv = [48 53 53 60 60 48]';% latitude of Alberta area
```

```
x=lon1; y=lat1;

xv=[xv;xv(1)]; yv=[yv;yv(1)];

in=inpolygon(x,y,xv,yv);

yr  = yr1(in);   mo = mo1(in);  dy = dy1(in);

hr  = hr1(in);   min = min1(in);

lat = lat1(in); lon = lon1(in);

ML=Ml1(in); MN=MN1(in); MB=Mb1(in);

MW=Mw1(in); MS=Ms1(in); MC=Mc1(in); MD=Md1(in);

MZ=Mz1(in); Mm=Mm1(in); Mpf=Mpf1(in); Tmpf=Tm1(in); Depth=Depth1(in);

dd=dd1(in); mf=mf1(in); Mw=new_Mw1(in); cf=cf1(in);

clear cf1 zf1 yr1 mo1 dy1 hr1 min1 lat1 lon1 Ml1 MN1 Mb1 Mw1 Ms1 Mc1 Md1
Mz1 Mm1 Mpf1 Tm1 Depth1 dd1 mf1 new_Mw1 x y xv yv te ts itw;

%%%%%write ccsc_Alberta catalog%%%%%

sec=zeros(length(yr),1);

Dth_or=zeros(length(yr),1);

tf=ones(length(yr),1);

disp('generate dataset data_ccsc13');

data_ccsc13eq=dataset(yr,mo,dy,hr,min,sec,lat,lon,ML,MN,MB,MW,MS,MC,MD,M
Z,Mpf,Tmpf,Depth,Dth_or,dd,cf,mf,Mw,tf);

clear yr mo dy hr min sec lat lon ML MN MB Mw Ms Mc Md Mz Mpf Tmpf Depth
Dth_or dd mf Mnew Mm in MC MD MS MW MZ;

clear cf;

export(data_ccsc13eq,'file','ccsc13forcascEq.csv','Delimiter',',');

%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%updated_CCSC13westBlast%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

format='%4d %02d %02d %02d %02d  %7.3f  %9.3f  %5.2f %5.2f %5.2f %5.2f %
5.2f %5.2f %5.2f %5.2f %5.2f %5.2f %s  %06.2f %s  %1d  %3d  %5.2f  %5.2f
';
```

```
[yr1,mo1,dy1,hr1,min1,lat1,lon1,Mb1,MN1,Ml1,Ms1,Mc1,Md1,Mw1,Mm1,Mz1,Mpf1
,Tm1,Depth1,dd1,cf1,~,mf1,new_Mw1]=...

textread('C:\Users\luqi\Documents\MATLAB\CASC13\newboundaryCASC2\CCSC201
3_west_blast.txt',format,'headerlines',3);

%%%%%%specify polygon region in the vectors xv and yv%%%%%

xv = [-121 -121 -124 -124 -110 -110]'; % longitude of Alberta area

yv = [48 53 53 60 60 48]';% latitude of Alberta area

x=lon1; y=lat1;

xv=[xv;xv(1)]; yv=[yv;yv(1)];

in=inpolygon(x,y,xv,yv);

yr  = yr1(in);    mo = mo1(in);   dy = dy1(in);

hr  = hr1(in);    min = min1(in);

lat = lat1(in); lon = lon1(in);

ML=Ml1(in); MN=MN1(in); MB=Mb1(in);

MW=Mw1(in); MS=Ms1(in); MC=Mc1(in); MD=Md1(in);

MZ=Mz1(in); Mm=Mm1(in); Mpf=Mpf1(in); Tmpf=Tm1(in); Depth=Depth1(in);

dd=dd1(in); mf=mf1(in); Mw=new_Mw1(in); cf=cf1(in);

clear cf1 zf1 yr1 mo1 dy1 hr1 min1 lat1 lon1 Ml1 MN1 Mb1 Mw1 Ms1 Mc1 Md1
Mz1 Mm1 Mpf1 Tm1 Depth1 dd1 mf1 new_Mw1 x y xv yv te ts itw;

%%%%%write ccsc_Alberta catalog%%%%%

sec=zeros(length(yr),1);

Dth_or=zeros(length(yr),1);

tf=2*ones(length(yr),1);

disp('generate dataset data_ccsc13blast');

data_ccsc13blast=dataset(yr,mo,dy,hr,min,sec,lat,lon,ML,MN,MB,MW,MS,MC,M
D,MZ,Mpf,Tmpf,Depth,Dth_or,dd,cf,mf,Mw,tf);

clear yr mo dy hr min sec lat lon ML MN MB Mw Ms Mc Md Mz Mpf Tmpf Depth
Dth_or dd mf Mnew Mm in MC MD MS MW MZ;

clear cf;
```

```
export(data_ccsc13blast,'file','ccsc13forcascblast.csv','Delimiter',',')
;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%Section4: Complilation of CASC13catalog%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

data=[data_GSC; data_AGS; data_ccsc];

Data=sortrows(data,{'yr','mo','dy','hr','min','sec'});

clear data ans;

export(Data,'file','Alberta_Composite_Catalog_2013.csv','Delimiter',',')
;

%%%%%%%compare_magt.m %%%%%%%%%%%%%%%%%%%%%%%%%%%%

function [ML MN MB Mw Ms Mc Md Mz Mpf Tmpf mf Mnew] =
compare_magt(mag,magt)

%convert different types of magnitude scale to moment magnitude

% The functions I choose here is from Azadeh Fereidoni (2012)

iml=strcmpi(magt,'Ml'); ML=mag.*iml;

imn=strcmpi(magt,'MN'); MN=mag.*imn;

imb=strcmpi(magt,'mb_Lg'); MB=mag.*imb;

imw=or(strcmpi(magt,'Mw'),strcmpi(magt,'Mwp')); Mw=mag.*imw;

ims=strcmpi(magt,'Ms'); Ms=mag.*ims;

imc=strcmpi(magt,'Mc'); Mc=mag.*imc;

imd=strcmpi(magt,'Md'); Md=mag.*imd;

imz = strcmp(magt,''); Mz = mag.*imz;

Mnew=zeros(length(ML),1);

mf=zeros(length(ML),1);

Mpf=zeros(length(ML),1);

Tmpf=cell(length(ML),1);

for i=1:length(ML)
```

```
if iml(i)==1
    Mnew(i)=ML(i)+0.12;
    mf(i)=0.12;
    Mpf(i)=ML(i);
    Tmpf{i}='ML';
elseif imn(i)==1
    Mnew(i)=MN(i)+0.05;
    mf(i)=0.05;
    Mpf(i)=MN(i);
    Tmpf{i}='MN';
elseif imb(i)==1
    Mnew(i)=MB(i)-0.06;
    mf(i)=-0.06;
    Mpf(i)=MB(i);
    Tmpf{i}='MB';
elseif imw(i)==1
    Mnew(i)=Mw(i);
    mf(i)=0;
    Mpf(i)=Mw(i);
    Tmpf{i}='Mw';
elseif ims(i)==1
    Mnew(i)=0.81*Ms(i)+1.3;
    mf(i)=1.3;
    Mpf(i)=Ms(i);
    Tmpf{i}='Ms';
elseif imc(i)==1
    Mnew(i)=0.96*Mc(i)+0.19;
```

```
        mf(i)=0.19;
        Mpf(i)=Mc(i);
        Tmpf{i}='Mc';
    elseif imd(i)==1
        Mnew(i)=0.96*Md(i)+0.19;
        mf(i)=0.19;
        Mpf(i)=Md(i);
        Tmpf{i}='Md';
    elseif imz(i)==1
        Mnew(i)=-9.99;
        mf(i)=0;
        Mpf(i)=Mz(i);
        Tmpf{i}='Mz';
    else
        Mnew(i)=-9.99;
        mf(i)=0;
        Mpf(i)=Mz(i);
        Tmpf{i}='Mz';
    end
end
disp([iml imn])
end
```

Appendix D. Matlab Script of Estimation M_c in time and space

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%% The Study of Magnitude Completeness Distribution%%%%%%%%%%
%%%%%%%%%%%%%%%%%%of Alberat and its surrounding area%%%%%%%%%%%%%%%
```

```
%This script will study the changes of seismic stations of Earthquake

%Canada since 1985. According to the distribution of seismic stations in different time period, a method based on the distance to the fourth

%closest station is applied to calculate the magnitude completeness values in space and temporal.

Clear

clc

%% import GSC station list

% using function importGSCstns to import the whole GSC station list used

% for AB province

%    Sta: text (%s)

%    Name: text (%s)

%    Prov: text (%s)

%    stnLat: double (%f)

%    stnLon: double (%f)

%    Network: text (%s)

%    OnDate: datetimes (%{MM/dd/yyyy}D)

%    offDate: datetimes (%{MM/dd/yyyy}D)

%    Status: text (%s)

[Sta,Name,Prov,stnLat,stnLon,Network,OnDate,offDate,Status] =...

    importGSCstns('filteredGSCformatlab.csv');

% manipulate datetime vector OnDate

%change OnDate<=1985-01-01 to 1985-01-01

for i=1:length(OnDate)

    if datenum(OnDate(i))<datenum('01/01/1985','MM/dd/yyyy')

        OnDate(i)=datetime('01/01/1985','Format','MM/dd/yyyy');

    end

end
```

```
%calculate month duration between StartDate and 1985-01-01

stnmonths=months(datetime(1985,01,01),OnDate);

%calculate month duration between EndDate and 1985-01-01

stnendmonths=months(datetime(1985,01,01),offDate);

for i=1:length(stnendmonths)

    if stnendmonths(i)==7368;

        stnendmonths(i)=nan;

    end

end

clear i

%% Investigate how to devide Time Periods based on the Increasing No. of
GSC stations

%graphic of stations and their working duration

%Output is the "The Time Period Distribution of GSC stations Figure"

x=1:22;

%y1 means the end month of stations

y1=[NaN(21,1); stnendmonths(22)];

% y is the matrix with start month and end month of all 22 stations

y=[stnmonths y1];

createGSCStnfigure(x,y);

clear y1 x y i

%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%Investigate Magnitude Completeness based on the divided Time Period%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%Time Period

%1985.01 - 1988.12    8
```

```
%1989.01 - 1999.12    9 (SES ended; WALA and YkW3 added)

%2000.01 - 2009.12    14

%2010.01 - 2012.12    19

%2013.01 - 2013.12    21

% import GSCstationTimeTable.xlsx, which includes a table of these 22 stations

% and flag numbers to note their working durations

%0 : not working

%1 : on working

%changing time period will have to regenerate the GSCstationTimeTable.xlsx

GSCstn=importStnList('GSCstationTimeTable.xlsx','sheet1');

p1=logical(GSCstn.p1);

p2=logical(GSCstn.p2);

p3=logical(GSCstn.p3);

p4=logical(GSCstn.p4);

p5=logical(GSCstn.p5);

%load grid center locations

load gridcenters.mat lat lon

% 1) D4 and mc from GSC catalog

D4p1=Dist(stnLat(p1),stnLon(p1),lat,lon);

D4p2=Dist(stnLat(p2),stnLon(p2),lat,lon);

D4p3=Dist(stnLat(p3),stnLon(p3),lat,lon);

D4p4=Dist(stnLat(p4),stnLon(p4),lat,lon);

D4p5=Dist(stnLat(p5),stnLon(p5),lat,lon);

D4_GSC=[D4p1 D4p2 D4p3 D4p4 D4p5];

mc=zeros(242,5);

a=82.398;
```

```
b=132.16;

for i=1:5

    for j=1:242

  mc(j,i)=(D4_GSC(j,i)+a)/b;

      if mc(j,i)>3.5;

          mc(j,i)=3.5;

      end

    end

end

xlswrite('McofGSC.xlsx',[lat lon mc],'sheet1')

xlswrite('McofGSC.xlsx',[lat lon D4_GSC],'sheet2')

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%%%% The Study of Magnitude Completeness Distribution%%%%%%%%%%

%%%%%%%%%%%    of Alberat and its surrounding area for AGS   %%%%%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%Objects: to calculate the distance(D4) between each center location of
the Alberta 242

%grids and the fourth closed staion of the AGS2006-2010 list

%Input

%1) group of vectors include: station name, station latitude and
longitude,station open date and closed date, station status

%2) vectors of grid center points Output

% vectors of D4 in different time period

clear

clc

%% import AGS station list

% using function importGSCstns to import the whole GSC station list used

% for AB province
```

```
%   Sta: cell
%   stnLat: double (%f)
%   stnLon: double (%f)
%   Network: cell
%   OnDate: cell
%   offDate: cell
%   Status: cell
[Sta,stnLat,stnLon,Network,onDate,offDate,Status] = ...
    importAGSstns('stationAGS.xlsx');
% manipulate datetime vector OnDate
%change onDate offDate to datetime
OnDate=datetime(onDate,'Format','MM/dd/yyyy');
OffDate=datetime(offDate,'Format','MM/dd/yyyy');
clear onDate offDate
% find Not-a-Time elements in OffDate and change these elements to
% '12/31/2010'
tf=isnat(OffDate);
OffDate(tf)='12/31/2010';
%calculate month duration between StartDate and 2006-01-01
stnmonths=months(datetime(2006,01,01),OnDate);
%calculate month duration between EndDate and 2006-01-01
stnendmonths=months(datetime(2006,01,01),OffDate);
for i=1:length(stnendmonths)
    if stnendmonths(i)==59;
        stnendmonths(i)=nan;
    end
end
```

```
save AGSstn.mat

%% Investigate how to devide Time Periods based on the Increasing No. of
GSC stations

%graphic of stations and their working duration

%Output is the "The Time Period Distribution of GSC stations Figure"

x=1:53;

y=[stnmonths stnendmonths];

createAGSfigure(x,y)

clear x y

print(gcf,'-dpng','-r600','AGSstnTimePeriod.png');

%% import AGS Time Period Table

AGSTimeTable = importAGSstnTimeTable('AGSstationTimeTable.xlsx');

StnName=AGSTimeTable.stnName;

% The first time period is from 2006  to 2009.06-01, 37 stations totally

p1=logical(AGSTimeTable.p1);

% The second time period is from 2009-06-01 to 2010   44 stations
totally

p2=logical(AGSTimeTable.p2);

clear AGSTimeTable

%load grid center locations

load gridcenters.mat lat lon

%%

% 1) D4 and mc from AGS catalog

D4p1=Dist(stnLat(p1),stnLon(p1),lat,lon);

D4p2=Dist(stnLat(p2),stnLon(p2),lat,lon);

D4_AGS=[D4p1 D4p2];

mc=zeros(242,2);

a=82.398;
```

```
b=132.16;

for i=1:2

    for j=1:242

  mc(j,i)=(D4_AGS(j,i)+a)/b;

      if mc(j,i)>3.5;

          mc(j,i)=3.5;

      end

    end

end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%%%% The Study of Magnitude Completeness Distribution%%%%%%%%%%

%%%%%%%%%%%    of Alberat and its surrounding area for NMX   %%%%%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%Objects: to calculate the distance(D4) between each center location of
the Alberta 242

%grids and the fourth closed staion of the NMX list as beginning of2015

%Input

%1) group of vectors include: station name, station latitude and
longitude,station open date and closed date, station status

%2) vectors of grid center points Output

% vectors of D4 in different time period

Clear

clc

%% import NMX station list

% using function importGSCstns to import the whole GSC station list used

% for AB province

%   Sta: cell

%   stnLat: double (%f)
```

```
%   stnLon: double (%f)
[Sta,stnLat,stnLon] = ...
    importNMXstn('NMXstations.xlsx','sheet1',2,55);
save NMXstn.mat
%% load grid center locations
load gridcenters.mat lat lon
%%  1) D4 and mc from NMX catalog
D4=Dist(stnLat,stnLon,lat,lon);
mc=zeros(242,1);
a=82.398;
b=132.16;
for i=1:242
  mc(i)=(D4(i)+a)/b;
      if mc(i)>3.5;
          mc(i)=3.5;
      end
end
%% Export D4 and mc matrix of NMX
xlswrite('McofNMX.xlsx',[lat lon mc],'sheet1')
function D4= Dist(stnlat,stnlon,lat,lon)
%DIST Summary of this function goes here
%   Detailed explanation goes here
m=length(lat);
n=length(stnlat);
d=zeros(n,1);
D4=zeros(m,1);
for i=1:m
```

```
    for j=1:n
        d(j)=distance(lat(i),lon(i),stnlat(j),stnlon(j));
    end
    D4(i)=dist4(d);
end
D4=deg2km(D4);
```

Appendix E. Magnitude Completeness Grid

latitude	longitude	1985-1989	1990-1999	2000-2006	2007-2009	2010	2011-2013	2014-2015
58.75	-120.5	3.50	3.50	3.50	3.50	3.02	3.02	2.67
58.25	-120.5	3.50	3.50	3.50	3.50	2.62	2.62	2.37
57.75	-120.5	3.50	3.50	3.50	3.50	2.31	2.31	2.31
57.25	-120.5	3.50	3.50	3.50	3.50	2.46	2.46	2.01
56.75	-120.5	3.50	3.50	3.50	3.26	2.75	2.75	1.95
56.25	-120.5	3.50	3.50	3.50	3.12	2.98	2.98	2.05
55.75	-120.5	3.50	3.50	3.50	3.16	2.75	2.75	1.72
55.25	-120.5	3.50	3.50	3.40	3.17	2.59	2.59	1.47
54.75	-120.5	3.50	3.50	3.02	2.99	2.50	2.85	1.62
54.25	-120.5	3.50	3.50	2.65	2.59	2.51	2.58	1.98
53.75	-120.5	3.50	3.50	2.71	2.61	2.31	2.56	2.19
53.25	-120.5	3.50	3.50	2.76	2.40	2.36	2.40	2.32
52.75	-120.5	3.50	3.50	2.43	2.08	2.08	2.43	2.53
52.25	-120.5	3.31	3.31	2.16	2.16	2.16	2.16	2.18
51.75	-120.5	3.50	3.50	1.83	1.96	1.96	1.83	1.96
51.25	-120.5	3.50	3.50	1.87	1.98	1.98	1.87	1.98

50.75	-120.5	3.50	3.50	1.91	1.93	1.93	1.91	1.93
50.25	-120.5	3.50	3.50	2.12	2.27	2.27	2.12	2.27
49.75	-120.5	3.50	3.50	2.45	2.67	2.67	2.45	2.67
49.25	-120.5	3.50	3.50	2.81	2.81	2.81	2.81	2.68
48.75	-120.5	3.50	3.50	3.19	3.19	3.19	3.19	3.03
48.25	-120.5	3.50	3.50	3.50	3.50	3.50	3.50	3.40
58.75	-119.5	3.50	3.50	3.50	3.50	3.19	3.19	2.42
58.25	-119.5	3.50	3.50	3.50	3.50	2.83	2.83	2.17
57.75	-119.5	3.50	3.50	3.50	3.50	2.50	2.50	2.07
57.25	-119.5	3.50	3.50	3.50	3.50	2.37	2.37	2.08
56.75	-119.5	3.50	3.50	3.50	3.50	2.51	2.51	1.95
56.25	-119.5	3.50	3.50	3.50	3.35	2.87	2.87	1.63
55.75	-119.5	3.50	3.50	3.50	3.04	2.82	3.18	1.46
55.25	-119.5	3.50	3.50	3.32	2.89	2.43	3.05	1.29
54.75	-119.5	3.50	3.50	2.99	2.84	2.55	2.84	1.59
54.25	-119.5	3.50	3.50	2.98	2.48	2.44	2.59	1.85
53.75	-119.5	3.50	3.50	2.91	2.35	2.07	2.57	2.05
53.25	-119.5	3.50	3.50	2.51	2.17	2.17	2.25	1.97
52.75	-119.5	3.50	3.50	2.13	1.78	1.78	2.13	2.17
52.25	-119.5	3.50	3.50	1.78	1.78	1.78	1.78	2.26
51.75	-119.5	3.50	3.50	1.49	1.49	1.49	1.49	2.20
51.25	-119.5	3.50	3.50	1.61	1.61	1.61	1.61	2.00
50.75	-119.5	3.50	3.50	1.83	1.83	1.83	1.83	1.90
50.25	-119.5	3.50	3.50	1.94	2.14	2.14	1.94	2.14

49.75	-119.5	3.50	3.50	2.20	2.44	2.44	2.20	2.44
49.25	-119.5	3.50	3.50	2.60	2.60	2.60	2.60	2.40
48.75	-119.5	3.50	3.50	3.01	3.01	3.01	3.01	2.79
48.25	-119.5	3.50	3.50	3.42	3.29	3.29	3.42	3.19
58.75	-118.5	3.50	3.50	3.50	3.50	3.43	3.43	2.75
58.25	-118.5	3.50	3.50	3.50	3.50	3.11	3.11	2.59
57.75	-118.5	3.50	3.50	3.50	3.50	2.82	2.82	2.39
57.25	-118.5	3.50	3.50	3.50	3.39	2.58	2.59	2.20
56.75	-118.5	3.50	3.50	3.50	3.33	2.41	2.42	1.99
56.25	-118.5	3.50	3.50	3.50	3.09	2.68	2.68	1.75
55.75	-118.5	3.50	3.50	3.50	2.74	2.69	3.08	1.64
55.25	-118.5	3.50	3.50	3.50	2.49	2.41	3.19	1.52
54.75	-118.5	3.48	3.48	3.34	2.77	2.44	2.77	1.48
54.25	-118.5	3.49	3.49	2.93	2.52	2.35	2.85	1.64
53.75	-118.5	3.50	3.50	2.80	2.11	1.93	2.50	1.88
53.25	-118.5	3.50	3.50	2.38	1.91	1.91	2.29	1.72
52.75	-118.5	3.50	3.50	1.97	1.66	1.66	1.97	1.73
52.25	-118.5	3.37	3.37	1.55	1.55	1.55	1.55	1.75
51.75	-118.5	3.50	3.50	1.15	1.15	1.15	1.15	1.85
51.25	-118.5	3.50	3.50	1.42	1.42	1.42	1.42	2.07
50.75	-118.5	3.50	3.49	1.84	1.84	1.84	1.84	1.97
50.25	-118.5	3.50	3.32	2.18	2.18	2.18	2.18	2.26
49.75	-118.5	3.50	3.20	2.58	2.11	2.11	2.58	2.58
49.25	-118.5	3.50	3.15	2.78	2.53	2.53	2.78	2.78

48.75	-118.5	3.50	3.50	3.04	2.83	2.83	3.04	3.04
48.25	-118.5	3.50	3.50	3.34	2.96	2.96	3.34	3.26
58.75	-117.5	3.50	3.50	3.50	3.50	3.50	3.50	2.74
58.25	-117.5	3.50	3.50	3.50	3.50	3.33	3.33	2.77
57.75	-117.5	3.50	3.50	3.50	3.38	3.19	3.19	2.53
57.25	-117.5	3.50	3.50	3.50	3.44	2.99	2.99	2.16
56.75	-117.5	3.50	3.50	3.50	3.30	2.77	2.86	1.83
56.25	-117.5	3.50	3.50	3.50	2.90	2.58	2.80	1.67
55.75	-117.5	3.50	3.50	3.50	2.68	2.50	2.99	1.56
55.25	-117.5	3.50	3.50	3.46	2.29	2.26	3.23	1.49
54.75	-117.5	3.50	3.50	3.09	2.47	2.31	3.05	1.55
54.25	-117.5	3.50	3.50	2.98	2.41	2.27	2.82	1.49
53.75	-117.5	3.50	3.50	2.75	2.00	2.00	2.57	1.66
53.25	-117.5	3.50	3.50	2.40	1.62	1.62	2.40	1.44
52.75	-117.5	3.50	3.50	1.99	1.70	1.70	1.99	1.33
52.25	-117.5	3.33	3.33	1.59	1.54	1.54	1.59	1.43
51.75	-117.5	3.08	3.08	1.56	1.56	1.56	1.56	1.56
51.25	-117.5	3.33	3.29	1.75	1.75	1.75	1.75	1.75
50.75	-117.5	3.50	3.03	2.05	2.04	2.04	2.05	2.08
50.25	-117.5	3.50	2.82	2.33	2.31	2.31	2.33	2.31
49.75	-117.5	3.50	2.74	2.67	2.21	2.21	2.59	2.51
49.25	-117.5	3.50	3.15	2.61	2.54	2.54	2.61	2.60
48.75	-117.5	3.50	3.50	3.02	2.48	2.48	3.02	2.69
48.25	-117.5	3.50	3.50	3.43	2.40	2.40	3.43	2.95

58.75	-116.5	3.50	3.50	3.50	3.50	3.48	3.50	3.18
58.25	-116.5	3.50	3.50	3.50	3.50	3.50	3.50	2.82
57.75	-116.5	3.50	3.50	3.50	3.50	3.13	3.50	2.41
57.25	-116.5	3.50	3.50	3.50	3.50	2.79	3.42	2.00
56.75	-116.5	3.50	3.50	3.50	3.31	2.47	3.31	2.16
56.25	-116.5	3.50	3.50	3.50	3.18	2.58	3.27	1.77
55.75	-116.5	3.50	3.50	3.50	2.77	2.38	3.25	1.69
55.25	-116.5	3.50	3.50	3.50	2.38	2.08	3.36	1.84
54.75	-116.5	3.50	3.50	3.50	2.24	2.00	2.97	1.55
54.25	-116.5	3.50	3.50	3.14	2.12	2.12	2.88	1.73
53.75	-116.5	3.50	3.50	2.77	2.24	2.24	2.62	1.37
53.25	-116.5	3.50	3.50	2.41	1.93	1.93	2.41	1.11
52.75	-116.5	3.50	3.50	2.20	1.69	1.69	2.20	1.05
52.25	-116.5	3.50	3.50	2.05	1.84	1.84	2.05	1.19
51.75	-116.5	3.26	3.26	2.07	1.69	1.69	2.00	1.40
51.25	-116.5	2.96	2.94	2.20	1.89	1.89	1.89	1.56
50.75	-116.5	3.27	2.70	2.43	2.19	2.19	2.19	1.68
50.25	-116.5	3.50	2.54	2.49	2.33	2.33	2.35	1.92
49.75	-116.5	3.50	2.91	2.46	2.25	2.25	2.37	2.16
49.25	-116.5	3.50	3.30	2.82	2.20	2.20	2.46	2.34
48.75	-116.5	3.50	3.50	3.19	2.08	2.08	2.84	2.41
48.25	-116.5	3.50	3.50	3.50	1.94	1.94	3.23	2.58
58.75	-115.5	3.50	3.50	3.50	3.50	3.50	3.50	3.23
58.25	-115.5	3.50	3.50	3.50	3.50	3.37	3.50	2.81

57.75	-115.5	3.50	3.50	3.50	3.50	2.97	3.50	2.39
57.25	-115.5	3.50	3.50	3.50	3.50	2.57	3.50	1.97
56.75	-115.5	3.50	3.50	3.50	3.50	2.47	3.50	2.29
56.25	-115.5	3.50	3.50	3.50	3.34	2.62	3.38	1.91
55.75	-115.5	3.50	3.50	3.50	2.97	2.40	3.08	1.99
55.25	-115.5	3.50	3.50	3.50	2.62	2.31	3.49	1.77
54.75	-115.5	3.50	3.50	3.50	2.29	2.29	3.21	1.69
54.25	-115.5	3.50	3.50	3.39	2.04	2.04	3.04	1.44
53.75	-115.5	3.50	3.50	3.05	1.86	1.86	3.00	1.20
53.25	-115.5	3.50	3.50	2.79	1.82	1.82	2.75	0.88
52.75	-115.5	3.50	3.50	2.53	1.78	1.91	2.49	0.79
52.25	-115.5	3.44	3.44	2.31	1.99	2.03	2.27	0.96
51.75	-115.5	3.24	3.04	2.28	2.09	2.16	2.21	1.19
51.25	-115.5	3.10	2.66	2.62	2.01	2.11	2.33	1.10
50.75	-115.5	3.02	2.98	2.57	2.12	2.12	2.34	1.26
50.25	-115.5	3.02	3.00	2.86	2.22	2.22	2.55	1.58
49.75	-115.5	3.19	3.19	2.90	2.22	2.22	2.82	1.89
49.25	-115.5	3.50	3.50	3.13	1.87	1.87	2.89	2.26
48.75	-115.5	3.50	3.50	3.46	1.62	1.62	3.11	2.65
48.25	-115.5	3.50	3.50	3.50	1.52	1.52	3.47	2.82
58.75	-114.5	3.50	3.50	3.50	3.50	3.50	3.50	3.29
58.25	-114.5	3.50	3.50	3.50	3.50	3.30	3.50	2.89
57.75	-114.5	3.50	3.50	3.50	3.50	2.88	3.50	2.49
57.25	-114.5	3.50	3.50	3.50	3.50	2.46	3.50	2.20

56.75	-114.5	3.50	3.50	3.50	3.50	2.52	3.50	2.43
56.25	-114.5	3.50	3.50	3.50	3.23	2.30	3.23	2.16
55.75	-114.5	3.50	3.50	3.50	2.82	2.36	3.25	1.92
55.25	-114.5	3.50	3.50	3.50	2.42	2.42	3.50	1.78
54.75	-114.5	3.50	3.50	3.50	2.18	2.03	3.50	1.70
54.25	-114.5	3.50	3.50	3.50	2.30	1.77	3.27	1.32
53.75	-114.5	3.50	3.50	3.43	1.91	1.94	3.24	0.93
53.25	-114.5	3.50	3.50	3.19	1.64	2.18	3.15	0.88
52.75	-114.5	3.30	3.50	2.94	1.73	2.07	2.93	1.10
52.25	-114.5	3.02	3.33	2.80	1.69	2.06	2.72	1.10
51.75	-114.5	2.78	2.91	2.73	1.99	2.18	2.67	1.11
51.25	-114.5	2.80	2.80	2.74	1.94	2.38	2.54	0.78
50.75	-114.5	3.00	3.00	2.84	2.08	2.30	2.79	0.98
50.25	-114.5	3.25	3.25	3.19	2.46	2.51	3.01	1.40
49.75	-114.5	3.50	3.50	3.44	2.09	2.09	3.23	1.73
49.25	-114.5	3.50	3.50	3.50	1.81	1.81	3.44	2.14
48.75	-114.5	3.50	3.50	3.50	1.42	1.42	3.49	2.16
48.25	-114.5	3.50	3.50	3.50	1.06	1.06	3.50	2.31
58.75	-113.5	3.50	3.50	3.50	3.50	3.50	3.50	3.43
58.25	-113.5	3.50	3.50	3.50	3.50	3.30	3.50	3.05
57.75	-113.5	3.50	3.50	3.50	3.50	2.88	3.50	2.68
57.25	-113.5	3.50	3.50	3.50	3.50	2.55	3.50	2.54
56.75	-113.5	3.50	3.50	3.50	3.50	2.53	3.50	2.53
56.25	-113.5	3.50	3.50	3.50	3.17	2.61	3.49	2.54

55.75	-113.5	3.50	3.50	3.50	2.76	2.75	3.48	2.34
55.25	-113.5	3.50	3.50	3.50	2.44	2.33	3.50	2.12
54.75	-113.5	3.50	3.50	3.50	2.36	2.16	3.50	1.84
54.25	-113.5	3.50	3.50	3.50	2.23	1.97	3.50	1.49
53.75	-113.5	3.50	3.50	3.50	1.89	1.89	3.50	1.23
53.25	-113.5	3.50	3.50	3.50	2.07	2.07	3.50	1.22
52.75	-113.5	3.41	3.50	3.41	1.97	1.99	3.37	1.43
52.25	-113.5	3.30	3.32	3.30	1.95	1.99	3.20	1.60
51.75	-113.5	3.25	3.25	3.18	2.08	2.09	3.10	1.33
51.25	-113.5	3.29	3.29	3.27	2.28	2.31	3.07	1.11
50.75	-113.5	3.46	3.46	3.35	2.06	2.24	3.10	1.15
50.25	-113.5	3.50	3.50	3.49	2.38	2.13	3.21	1.47
49.75	-113.5	3.50	3.50	3.50	2.16	2.13	3.50	1.79
49.25	-113.5	3.50	3.50	3.50	1.82	1.82	3.50	2.19
48.75	-113.5	3.50	3.50	3.50	1.57	1.57	3.50	2.60
48.25	-113.5	3.50	3.50	3.50	1.31	1.31	3.50	2.65
58.75	-112.5	3.50	3.50	3.50	3.50	3.50	3.50	3.50
58.25	-112.5	3.50	3.50	3.50	3.50	3.39	3.50	3.28
57.75	-112.5	3.50	3.50	3.50	3.50	3.08	3.50	3.08
57.25	-112.5	3.50	3.50	3.50	3.50	2.92	3.50	2.92
56.75	-112.5	3.50	3.50	3.50	3.50	2.99	3.50	2.99
56.25	-112.5	3.50	3.50	3.50	3.38	3.06	3.50	2.94
55.75	-112.5	3.50	3.50	3.50	3.07	2.79	3.50	2.70
55.25	-112.5	3.50	3.50	3.50	2.80	2.38	3.50	2.35

54.75	-112.5	3.50	3.50	3.50	2.63	2.29	3.50	2.13
54.25	-112.5	3.50	3.50	3.50	2.44	2.32	3.50	1.86
53.75	-112.5	3.50	3.50	3.50	2.39	1.98	3.50	1.67
53.25	-112.5	3.50	3.50	3.50	2.43	2.34	3.50	1.71
52.75	-112.5	3.50	3.50	3.50	2.45	2.27	3.50	1.86
52.25	-112.5	3.50	3.50	3.50	2.46	2.46	3.50	1.97
51.75	-112.5	3.50	3.50	3.50	2.18	2.18	3.50	1.77
51.25	-112.5	3.50	3.50	3.50	2.34	2.04	3.50	1.62
50.75	-112.5	3.50	3.50	3.50	2.24	1.93	3.50	1.64
50.25	-112.5	3.50	3.50	3.50	2.46	1.88	3.50	1.82
49.75	-112.5	3.50	3.50	3.50	2.41	1.92	3.50	2.06
49.25	-112.5	3.50	3.50	3.50	2.09	2.06	3.50	2.40
48.75	-112.5	3.50	3.50	3.50	1.84	1.84	3.50	2.27
48.25	-112.5	3.50	3.50	3.50	1.67	1.67	3.50	2.18
58.75	-111.5	3.50	3.50	3.50	3.50	3.50	3.50	3.50
58.25	-111.5	3.50	3.50	3.50	3.50	3.50	3.50	3.50
57.75	-111.5	3.50	3.50	3.50	3.50	3.22	3.50	3.31
57.25	-111.5	3.50	3.50	3.50	3.50	3.32	3.50	3.32
56.75	-111.5	3.50	3.50	3.50	3.50	3.45	3.50	3.45
56.25	-111.5	3.50	3.50	3.50	3.50	3.32	3.50	3.30
55.75	-111.5	3.50	3.50	3.50	3.43	2.93	3.50	2.95
55.25	-111.5	3.50	3.50	3.50	3.21	2.56	3.50	2.72
54.75	-111.5	3.50	3.50	3.50	2.97	2.22	3.50	2.50
54.25	-111.5	3.50	3.50	3.50	2.92	2.14	3.50	2.28

53.75	-111.5	3.50	3.50	3.50	2.88	2.30	3.50	2.16
53.25	-111.5	3.50	3.50	3.50	2.66	2.61	3.50	2.15
52.75	-111.5	3.50	3.50	3.50	2.96	2.31	3.50	2.31
52.25	-111.5	3.50	3.50	3.50	2.79	2.39	3.50	2.37
51.75	-111.5	3.50	3.50	3.50	2.44	2.16	3.50	2.24
51.25	-111.5	3.50	3.50	3.50	2.54	1.76	3.50	2.14
50.75	-111.5	3.50	3.50	3.50	2.56	1.87	3.50	2.14
50.25	-111.5	3.50	3.50	3.50	2.68	1.92	3.50	2.27
49.75	-111.5	3.50	3.50	3.50	2.37	2.07	3.50	2.37
49.25	-111.5	3.50	3.50	3.50	2.44	1.96	3.50	2.04
48.75	-111.5	3.50	3.50	3.50	2.21	2.13	3.50	1.98
48.25	-111.5	3.50	3.50	3.50	2.13	2.13	3.50	2.13
58.75	-110.5	3.50	3.50	3.50	3.50	3.50	3.50	3.50
58.25	-110.5	3.50	3.50	3.50	3.50	3.50	3.50	3.50
57.75	-110.5	3.50	3.50	3.50	3.50	3.50	3.50	3.50
57.25	-110.5	3.50	3.50	3.50	3.50	3.50	3.50	3.50
56.75	-110.5	3.50	3.50	3.50	3.50	3.50	3.50	3.50
56.25	-110.5	3.50	3.50	3.50	3.50	3.50	3.50	3.50
55.75	-110.5	3.50	3.50	3.50	3.50	3.17	3.50	3.28
55.25	-110.5	3.50	3.50	3.50	3.49	2.83	3.50	3.14
54.75	-110.5	3.50	3.50	3.50	3.35	2.53	3.50	2.91
54.25	-110.5	3.50	3.50	3.50	3.41	2.49	3.50	2.74
53.75	-110.5	3.50	3.50	3.50	3.29	2.69	3.50	2.65
53.25	-110.5	3.50	3.50	3.50	2.96	2.95	3.50	2.64

52.75	-110.5	3.50	3.50	3.50	3.26	2.67	3.50	2.79
52.25	-110.5	3.50	3.50	3.50	3.09	2.43	3.50	2.84
51.75	-110.5	3.50	3.50	3.50	2.79	2.26	3.50	2.73
51.25	-110.5	3.50	3.50	3.50	2.84	2.19	3.50	2.63
50.75	-110.5	3.50	3.50	3.50	2.95	2.24	3.50	2.66
50.25	-110.5	3.50	3.50	3.50	2.73	2.38	3.50	2.72
49.75	-110.5	3.50	3.50	3.50	2.61	2.28	3.50	2.58
49.25	-110.5	3.50	3.50	3.50	2.89	2.39	3.50	2.51
48.75	-110.5	3.50	3.50	3.50	2.62	2.53	3.50	2.53
48.25	-110.5	3.50	3.50	3.50	2.64	2.38	3.50	2.64

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