**Analyses of earthquakes in the Western Quebec Seismic Zone using data from the
United States Transportable Array**

by

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**A thesis submitted to the Faculty of Graduate and Postdoctoral Affairs
in partial fulfillment of the requirements for the degree of**

Master of Science

in

Department of Earth Sciences

Carleton University

Ottawa, Ontario

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ABSTRACT

The present research investigates the efficacy of the additional seismic stations that were deployed in the Western Quebec Seismic Zone (WQSZ) as part of the US Transportable Array (USTA) during 2013-2015 in the determination of earthquake source parameters in this zone. The study is concentrated on the determination of hypocentre locations of three sets of data: the aftershock sequence of the 2010 Val-des-Bois earthquake; the aftershock sequence of the 2013 Ladysmith earthquake; and, 18 events of magnitude 3.0 or greater that occurred in the WQSZ from January 2013 to mid-July 2015. An attempt is also made to estimate the focal mechanisms of all events with $M_N \geq 3$ that occurred in the WQSZ during 2013-2015. The relocated hypocentres of the two aftershock sequences using the double-difference algorithm through the hypoDD program and the joint hypocentre determination through VELEST software shows insignificant changes in focal depths (toward shallower depths) and only slight variations in the trend of the seismicity (toward the southwest for the Val-des-Bois aftershock and toward the south-east for the Ladysmith aftershock). Relocation of 18 magnitude 3+ events using the standard travel times method demonstrates more reliable focal depths when both the Canadian National Seismograph Network and the USTA data are used. Although favourable coverage provided by the additional USTA can be slightly more effective in obtaining more accurate hypocentres for small earthquakes, the focal mechanism solutions are not remarkably changed when more data from the combined seismic network are used.

ACKNOWLEDGMENTS

I would first like to express my deep gratitude to my supervisors, Dr. Allison Bent and Dr. Dariush Motazedian, for their continuous support, patience, motivation and immense knowledge. They consistently allowed this study to be my own work, but steered me in the right direction whenever they thought I needed it.

Also, I must express my very profound gratitude to my loved ones, my parents for providing me with unfailing support and continuous encouragement throughout my years of study and with special thanks to my husband who provided moral support and my lovely son for his patience and tolerance.

This project is partially funded by the Public Safety Geoscience Program with logistical support from the Canadian Hazards Information Service, which both are part of Natural Resources Canada. Also, I obtained financial support from the Earth Sciences Department as a Teaching Assistant and Research Assistant and from the Ontario Graduate Scholarship program (OGS). Data from the USTA network were made freely available as part of the EarthScope USArray facility, operated by Incorporated Research Institutions for Seismology (IRIS) and supported by the National Science Foundation, under Cooperative Agreements EAR-0323309, EAR-0323311, EAR-0733069.

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1. INTRODUCTION

The Western Quebec Seismic Zone (WQSZ) is an intraplate environment in Eastern Canada with the seismic hazard rated as moderately high. This active seismic zone includes two population centres: Montréal, Québec, with a population of 3.3 million; and Ottawa, Ontario, with a population of about one million people.

Although large and deadly earthquakes are scarce in Eastern Canada, the WQSZ has historically experienced several large earthquakes. It was in this zone that the 1935 Timiskaming earthquake with M_w 6.1 (M_w is the magnitude as calculated using the moment magnitude scale from Hanks and Kanamori, 1979) and the 1944 Cornwall-Massena earthquake (M_w 5.8) occurred. The Val-des-Bois earthquake (M_w 5.2) on June 23, 2010 and the Ladysmith earthquake (M_w 4.6) on May 17, 2013 are two recent events that highlight the seismic potential of the zone.

Figure 1.1 shows the distribution of the historical seismic activity in the WQSZ during the time period of 1627 to 2015. The recurrence of a large earthquake in this zone could be more devastating today, due to the proximity to densely populated cities, which increases the level of seismic risk in this area (Figure 1.2).

Monitoring of the seismic activity in the WQSZ is already done well by the many stations that the Canadian National Seismograph Network (CNSN) has in this zone. The deployment of several US Transportable Array (USTA) stations installed from 2013 to 2015 resulted in an increase in the number of seismic stations and provided more data sets, which led to temporarily improved monitoring and research opportunities. The main goal of this study is to investigate whether the additional USTA stations lead to better observational constraints on the recent seismicity in this region.

Figure 1.1: Distribution of the historical seismic activity in the WQSZ (1627-2015). The data used for preparing the map were extracted from Earthquakes Canada, GSC, Earthquake Search (On-line Bulletin), <http://earthquakescanada.nrcan.gc.ca/stndon/NEDB-BNDS/bull-eng.php>, Nat. Res. Can., accessed June 2016, which contained data from 1985 to the end of 2015 and from Seismic Hazard Earthquake Epicentre File (SHEEF2010) used in the fifth generation seismic hazard maps of Canada. Halchuk, S., Allen, T.I., Rogers, G.C., and Adams, J. Geological Survey of Canada, open File 7724, 2015 (<http://geoscan.nrcan.gc.ca/>), which contained data from 1627 to the end of 2010. (The 1732 Montreal and the 1935 Timiskaming earthquakes were two large events with $M_w > 6.0$ that occurred in this zone.)

Figure 1.2: Simplified 2015 seismic hazard map of Eastern Canada, (source: <http://www.earthquakescanada.nrcan.gc.ca/hazard-alea/simphaz-en.php>). The Western Quebec Seismic Zone is marked as WQSZ, the Charlevoix Seismic Zone is marked as CSZ, and the Lower St. Lawrence Seismic Zone is denoted as LSZ.

The data set for this study was a compilation of three sets of events: the aftershock sequence from the 2010 Val-des-Bois earthquake; the aftershock sequence of the 2013 Ladysmith earthquake; and 18 events with magnitude 3.0 or greater ($M_N \geq 3.0$, $M_W \geq 2.5$, M_N is the Nuttli magnitude, which is derived by Nuttli for Eastern Canada, Nuttli, 1973. The value of M_W is estimated based on $M_W = m_N - 0.5$) that occurred from January 2013 to July 2015 in the WQSZ.

This study used a combination the new seismic data, such as waveforms and travel times from the USTA, and the existing data from the Canadian National Earthquake Database (CNED, which is mainly derived from the CNSN). The data from both networks were utilized to investigate any possible advantages in the determination of source parameters such as focal depths, epicentres and focal mechanisms.

1.1 MONITORING EARTHQUAKES IN CANADA BY THE CANADIAN NATIONAL SEISMOGRAPH NETWORK (CNSN)

There are more than 200 seismographs located across Canada that record local and global earthquakes. Natural Resources Canada (NRCan) operates 125 stations, which make up the CNSN. The Geological Survey of Canada (GSC) is the part of NRCan, operating its seismographs and more than 60 accelerographs and using the data that are gathered by the CNSN to determine the size and location of earthquakes. The remaining seismographs are part of university or government research networks.

The data from the CNSN is analyzed by the GSC, and the locations and magnitudes of earthquakes are calculated. All seismic information is reviewed by an analyst who informs emergency agencies and the general public if needed. These high-quality data sets are used to determine the seismic hazard, which is also used to improve the National Building Code of Canada (NBCC) provisions.

In this study, data from 42 CNSN stations located within or near the WQSZ, as shown in Figure 1.3, were used. Table 1.1 provides their locations. All information about the stations, including instrumentation, sample rates, channels recorded, etc., can be found in the CNSN

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Table 1.1: Locations of the CNSN seismographs within and near the WQSZ used in this study, (those stations located within the WQSZ are marked by *). Data were extracted from www.earthquakescanada.nrcan.gc.ca/stndon/CNSN-RNSC/stnbook-cahierstn/index-en.php.

Station Code	Long (°W)	Lat (°N)	Station Code	Long (°W)	Lat (°N)
*ALFO	74.88	45.63	*ALGO	78.05	45.95
BANO	77.93	45.02	BECQ	72.48	46.34
BUKO	79.39	45.44	DELO	77.62	44.52
DMCQ	72.07	48.97	DRWO	78.73	43.87
*FRNY	73.59	44.83	*KB10-60	76.18	45.39
KILO	79.72	48.49	LATQ	72.78	47.38
*LSQ1	76.15	45.79	MEDO	78.45	43.17
*MNTQ	73.62	45.50	NCB	74.22	43.97
*ORIO	75.51	45.45	PECO	76.99	43.93
*PEMO	77.25	45.68	PKRO	79.07	43.96
PLVO	77.07	45.04	STCO	79.17	43.21
STUQ	73.09	46.30	TORO	79.34	43.61
VLDQ	77.76	48.19	WLVO	78.39	43.92
EFO	79.31	43.09	*ORHO	75.54	45.46
*LDSQ	76.35	45.71	*BELQ	78.69	47.39
*CRLO	77.38	46.04	DPQ	72.78	46.68
*EEO	79.07	46.64	*GAC	75.48	45.70
*GRQ	75.86	46.61	KGNO	76.49	44.23
MOQ	72.25	45.31	*OTT	75.72	45.39
SADO	79.14	44.77	*TRQ	74.55	46.22
*VABQ	75.61	45.90	*WBO	75.27	45.00

1.2 US TRANSPORTABLE ARRAY (USTA)

The US Array is one of the components of the US National Science Foundation's EarthScope program facilities, which includes four major observatory components: (1) Reference Network; (2) Transportable Array (TA); (3) Flexible Array (FA); and (4) Magnetotelluric (MT) Array (www.usarray.org).

The USTA consists of 400 high-quality broadband seismographs and has been operating across the United States in temporary locations since 2007. The array has moved from west to east, with an approximately two-year residency in each place. They have a regular pattern of distribution with spacing about 70 km from each other. Although the main purpose of the USTA was subsurface structural studies, the seismic data recorded by these stations happen to be very useful for investigations of earthquakes for North America.

The USTA stations consist of three-component broadband seismometers collocated with other necessary equipment (such as signal processing, power and communications). All seismic data are transmitted to the Array Network Facility at the University of California-San Diego, to perform quality checks and are archived at the Incorporated Research Institutions for Seismology (IRIS) Data Management Center in Seattle, Washington, where everyone can access them (www.usarray.org/researchers/obs/transportable).

This study used data from 44 USTA stations that were deployed in Eastern Canada (4 of them were located in the US) during the eastward movement of the TA (2013-2015). Twenty of these stations were located in the WQSZ, which roughly doubling the number of stations in this zone. The concentration of the USTA stations was greater in the northern part of the WQSZ, where the density of CNSN stations is sparse. Therefore, the addition of more stations in this area can be more effective in seismic studies of this area. Figure 1.3 and Table 1.2 provide the seismic locations.

Table 1.2: Locations of the USTA seismographs in Eastern Canada, station locations were extracted from IRIS (<http://anf.ucsd.edu/>). Stations located within the WQSZ are marked by *.

Station Code	Long (°W)	Lat (°N)	Station Code	Long (°W)	Lat (°N)
H56A	76.26	44.59	*F55A	76.35	45.83
D46A	84.04	46.89	*F57A	74.69	45.81
D47A	83.10	47.06	F59A	72.78	45.85
D49A	81.36	47.28	G53A	78.62	45.12
D51A	79.37	47.09	G54A	78.09	45.39
*D52A	78.41	46.98	*G55A	76.72	45.25
*D53A	77.70	47.08	*G58A	74.05	45.15
*D54A	76.66	47.15	H52A	79.89	44.64
*D56A	74.76	47.05	H53A	78.58	44.57
D57A	73.89	47.02	H55A	77.18	44.55
E48A	82.16	46.48	I55A	77.68	44.22
E50A	80.74	46.42	*D55A	75.47	47.02
E51A	79.49	46.53	*H57A	75.39	44.46
*E52A	78.66	46.29	*H58A	74.18	44.42
*E53A	77.66	46.38	H60A	72.69	44.56
*E54A	77.19	46.43	*LONY	74.58	44.62
*E55A	76.06	46.45	*F58A	73.81	45.89
*E56A	75.03	46.54	D58A	72.88	47.09
*E57A	74.15	46.41	D50A	79.84	47.17
E58A	73.28	46.37	E59A	72.51	45.10
F51A	79.92	45.93	*G57A	74.99	45.10
F52A	79.32	45.79	G60A	72.33	45.09

1.3 OBJECTIVES OF THIS STUDY

Earthquakes as typical seismic sources are caused by rupture of the rock along a planar surface (fault). The rupture begins at a point that is the location of an earthquake and is known as the hypocentre (or focus), and the first seismic waves emanate from that point. The hypocentre can, therefore, be determined from the seismic wave's travel times.

The rupture propagates across the fault and extends to the surface. The point of focus below the earth's surface and the point above the focus on the earth's surface are called focal depth and epicentre, respectively. The fault plane orientation and the slip direction define the fault geometry, which is known as the focal mechanism and can be obtained from the polarity (the first motion) of body waves.

The primary objective of this study was the determination of some of the key source parameters, such as epicentre locations, focal depths and focal mechanisms, using the additional seismic data provided by the USTA for events occurring in the WQSZ from 2013 to 2015. For this investigation, we can conclude whether the increased station density arising from the USTA stations provided better constrained parameters. Three sets of earthquakes have been studied:

- Set #1: 45 Val-des-Bois late aftershocks (for the time period of 2013-2015) with a magnitude (M_N) range between 0.4 and 3.4;
- Set #2: 50 Ladysmith mainshock and aftershocks with a magnitude (M_N) range between 0.9 and 5.2;
- Set #3: other seismic events with magnitudes of 3.0 or greater that occurred from January 2013 through July 2015 in the WQSZ, as shown in Figure 1.4.

Set #3 also included five events of the aftershock sequence of the Ladysmith earthquake (20130517-A, 20130517-B, 20130517-C, 20130530 and 20130630 in Table 4.5) that were included in Set #2.

We focused on these two aftershock sequences, because it was thought that they included enough small earthquakes concentrated in a small area to make the study more valuable in

terms of determination of the relocated hypocentres due to the increase in the network coverage density. The analysis of these two aftershock sequences was done using the double-difference (DD) method through the hypoDD program (Waldhauser and Ellsworth, 2000) and the joint hypocenter determination (JHD) method through the VELEST program (Kissling, 1995).

The DD technique determines relatively accurate locations of events by minimizing the errors due to non-modelled velocity structures based on the differential of primary and secondary (P/S) wave travel times. The JHD method simultaneously calculates hypocentres, velocity model and station corrections.

The threshold of the magnitude of 3.0 for Set #3 was chosen to re-evaluate smaller magnitude events, because the hypocentral locations and focal mechanism solutions for larger earthquakes (with magnitude greater than 4.0) can be reliably determined using the CNSN, but not so smaller events, which usually do not generate enough data.

The hypocentre relocation of the larger events in Set #3 was done using the standard travel time inversion method and the focal mechanism solutions were done using the polarities of the first motions.

The seismic data from the USTA were combined with the seismic data from the CNSN and used to determine the hypocentre locations for all three datasets using different techniques and focal mechanisms for Set #3.

Chapter 2 of this thesis provides a general description of the geological setting and historical seismicity of the WQSZ. Chapter 3 explains the data sets used and methodology applied in this study, including the hypoDD, VELEST, DAN and FOCMEC programs. The

relocated epicentres using both the CNSN and the USTA data sets and a comparison of the results with those in the GSC catalogue are described in Chapter 4. The relocated focal depths using both the CNSN and the USTA data sets and a comparison of the results with those in the GSC catalog are reported in Chapter 5; and, the focal mechanisms (for larger events) obtained in both cases are discussed in Chapter 6. Finally, Chapter 7 summarizes the source parameters obtained in this study and makes some general conclusions based on the results of the study.

Figure 1.4: Distribution of three series of studied events that occurred from 2013 to 2015 in the WQSZ. Purple circles represent aftershocks of the 2010 Val-des-Bois earthquake, green circles show the aftershock sequences of the 2013 Ladysmith earthquake, and brown circles display events with $M_N \geq 3.0$. The epicentres of the Ladysmith and Val-des-Bois earthquakes are shown with red stars (1 and 2, respectively). The size of the circles is proportional to the magnitude.

2. GEOLOGICAL AND SEISMOLOGICAL SETTING OF THE WQSZ

2.1 INTRODUCTION

It is generally accepted that the most of the world's earthquakes can be explained by the theory of plate tectonics. Although the majority of the large and destructive earthquakes occur in active plate-margin settings, some earthquakes, which can still cause devastation to property and loss of human life, take place away from plate boundaries (Adams and Basham, 1989). Intraplate regions frequently experience various levels of seismic activity. In contrast to plate-margin seismicity, the cause of intraplate seismicity is not well understood, because the strain rates in intraplate regions usually are lower than those in plate boundaries. Hence, major earthquakes rarely occur, the seismogenic faults are minor in nature, and seismic activities are scattered within the plates.

The stable part of North America, including Eastern Canada (38°N - 90°N and 90°W - 45°W) (Halchuk et al., 2015), the northeastern and north-central United States and western Greenland and many offshore regions (Bent, 2009), generally exhibits a low rate of seismic activity. However, some parts of this region do experience large and damaging earthquakes that can endanger inhabitants and negatively affect the economy.

According to Natural Resources Canada (www.earthquakescanada.nrcan.gc.ca/zones/eastern-en.php), the rate of seismic activity in Eastern Canada is about 450 earthquakes recorded per year, with, on average, four events exceeding magnitude 4, 30 events greater than magnitude 3 and about 25 events that are reported as felt. On average, three events larger than magnitude 5 will occur during a

decade in this region. Magnitude 5 is the magnitude level usually considered to be the damage threshold.

Instrumental recordings of earthquakes in Eastern Canada show that the earthquake activity is concentrated in several clusters. The Western Quebec Seismic Zone (WQSZ) is one of these seismic clusters and was first defined by Basham et al., (1979) using contouring of the epicentral distribution (Figure 2.1). The approximate dimensions of this zone are 160 km in width and 500 km in length with a northwest trend that extends from the Adirondack Highlands of upstate New York (43.5°N, 73.5°W) to the Timiskaming region of Québec, Canada (47.5°N, 79°W). In spite of being a generally wide zone, seismicity is not uniform and is concentrated in some narrower subzones with 50-60 km widths in this zone (Forsyth, 1981; Adams and Bashan, 1991).

This region experiences about three earthquakes with magnitudes > 4.5 per decade, with the most recent one being the 2013 Ladysmith earthquake with $M_w 4.6$ (Bent et al., 2015). Some of the historically significant earthquakes that have occurred in the WQSZ are listed in Section 2.4.

2.2 BACKGROUND GEOLOGY

The WQSZ, which is located in the southwestern Grenville Province of the Canadian Shield, was formed over a long time period. Its initial age of development was 2.8 Ga inside the Superior Province (Laurentian Craton) and along the track of the Great Meteor hot spot 115 Ma (Adams and Basham, 1991).

The Mesoproterozoic Grenville orogeny (1.2-1.0 Ga) and the Silurian-Permian Appalachian orogeny (460-260 Ma), which are the two major orogenic belts, cut across this region (Faill, 1997) (Figure 2.2).

Figure 2.1: Seismicity of Eastern Canada. The approximate outline of the WQSZ is defined by the red dashed-line (WQSZ) (Basham et al., 1982). The other seismic zones are: Southern Great Lakes Seismic Zone (SGL), Charlevoix Seismic Zone (CHV), Lower St. Lawrence Seismic Zone (LSL), Northern Appalachians Seismic Zone (NAP), and Laurentian Slope Seismic Zone (LSP). (Source: www.earthquakescanada.nrcan.gc.ca/zones/eastcan-en.php). The data were extracted from Earthquakes Canada, GSC, Earthquake Search (On-line Bulletin), <http://earthquakescanada.nrcan.gc.ca/stndon/NEDB-BNDS/bull-eng.php>, Nat. Res. Can., accessed June 2016, which contained data from 1985 to the end of 2015 and from Seismic Hazard Earthquake Epicentre File (SHEEF2010) used in the fifth generation seismic hazard maps of Canada. Halchuk, S., Allen, T.I., Rogers, G.C., and Adams, J. Geological Survey of Canada, open File 7724, 2015 (<http://geoscan.nrcan.gc.ca/>), which contained data from 1627 to the end of 2010.

The northern part of the study area consists of the Superior Province, the largest piece of Archean continental crust on Earth. Formation of the Superior Province was the result of preliminary crust conjugation during subduction related to a prograding arc system (Ludden and Hynes, 2000).

Figure 2.2: Geologic map of southeastern Canada, after Faill [1997]. The Grenville and the Appalachian orogenic belts are identified in the region. The continuous thick lines show the Iapetan rifting arms. The dashed line represents the approximate location of the Great Meteor Hot spot track (Heaman and Kjaarsgaard, 2000).

The Grenville Province in the south of the study area is subdivided into three basic geologic units: the Ontario and Quebec gneiss belts located in the northwestern part and consisting of northwesterly and northeasterly directed quartzo-feldspathic gneisses; the supra crustal Grenville rocks with north-south and northeast trends located in the central part (Forsyth, 1981) (Figure 2.3); and, the granulite facies metamorphic rocks and anorthosite massifs. Wynne-Edwards (1972) termed the supra crustal Grenville rocks as the central meta-sedimentary belt (CMB). This group consists of amphibolite grade marbles, quartzites, paragneisses and, meta-volcanics. Studies by Doig (1977) show an age transition from 2450 to 2850 Ma in the southeastern part of the Grenville Province to 2000 Ma in the north-central Ontario gneiss belt and 1000-1250 Ma in the CMB. The Grenville Supergroup rocks were deposited on the margins of the Ontario and Quebec gneiss belts between 1250 and 1400 Ma ago. The Grenville orogeny, which occurred about 1100 Ma (Barton and Doig, 1973, 1974), metamorphosed these sediments to amphibolite and granulite grade. Wynne-Edwards (1972) suggested that most of the western Quebec seismic activity happened in the northeastern and northwestern borders of the CMB.

Figure 2.3: Seismicity and geological features in and near the WQSZ. The approximate outline of the WQSZ is denoted by the blue line, the subdivisions of the geological province are shown by dashes. Cataclastic/mylonite zones are shown by lined area and anorthosite bodies are identified by stippled areas. The numbers 1 and 2 display the Winchester Springs fault and the Gloucester fault, respectively. Area 3 shows a narrow north-south trending feldspar gneiss, area 4 shows cataclastic effects, area 5 shows the Colton-Carthage mylonite zone (Forsyth, 1981, with permission). Some of large events are shown on the map.

The Grenville orogeny, which is mainly exposed along the southeastern edge of the Canadian Shield (the primary exposure of this largest mountain-building event is the Grenville Province), extends under the internal platform Phanerozoic sedimentary rocks. The Grenville orogeny is similar to the modern Alpine-Himalayan orogeny with respect to the tectonic setting, and this resemblance suggests that widely similar continent-continent collisional processes have formed both of them (Carr et al., 2000). The crust of the Grenville Province, which is thinner in the vicinity of the WQSZ, has various thicknesses between 30 and 48 km (Eaton et al., 2006).

The Iapetus Ocean (between 600 and 400 Ma) was located between the Laurentia, Baltica and Avalonia paleocontinents in the late Neoproterozoic and early Paleozoic Eras. It opened between Laurentia and southwestern Gondwana during their separation (Prigmore et al., 1997).

Mafic dykes and normal faults along the Ottawa-Bonnechere graben are interpreted as evidence for rifting during the opening of the Iapetus 650 Ma (Kamo et al., 1995). The Iapetus Ocean closed during widespread continental collision, and it completely disappeared 420 Ma with the assembly of Laurasia, the northern part of Pangaea.

The final assembly of Pangaea was the culmination of numerous orogenic events, such as the Ordovician-Silurian Taconic orogeny, the Middle and Late Devonian Acadian orogeny, and the Permian Allegheny orogeny, forming the 3000+ km long Appalachian orogen in eastern North America (Faill, 1997).

Investigations have shown that the Great Meteor Hotspot track (developed from the northern Atlantic Ocean to Nunavut in Northern Canada) extends northward across North

America and passes through the WQSZ (Crough, 1981; Morgan, 1983; Sleep, 1990; McHone, 1996). The ages of crystallization of intrusive bodies from hotspot activity increased uniformly from southeast toward northwest (Heaman and Kjaarsgaard, 2000) and match the hotspot track direction.

There are some other surface features that could be related to the hotspot including intermediate-volume alkaline lavas near the edge of the craton and throughout the Appalachian orogeny (Zartman, 1977; Eby, 1984) and small-volume kimberlite eruptions (Heaman and Kjaarsgaard, 2000). The kimberlite bodies were originally formed in the upper mantle and intruded into the lithosphere in the craton. These changes in hotspot processes indicate that kimberlitic melts progressed to more massive crustal magmatism during the hotspot's interaction with thinner lithosphere during the overriding plate motion (Ma, 2009).

2.3 SEISMOLOGICAL SETTING

The responsible processes for intraplate seismicity in Eastern Canada have been studied by Hasegawa and Adams (1981) and Hasegawa et al. (1985). These studies reported that the plate tectonic processes are a possible source of generated stresses that cause seismicity and are likely related to the spreading of the Mid-Atlantic Ridge.

It has been inferred that a compressive stress field that is oriented northeast-to-east generates earthquakes in Eastern Canada. This regional stress field reactivates weak crustal regions where there are failed rift systems or old fault zones (Kumarapeli and Saull, 1966).

In southeastern Canada (onshore), the majority of the seismic activity is concentrated in four areas, as shown in Figure 2.1: the WQSZ, the Lower St. Lawrence Seismic Zone, the Charlevoix Seismic Zone and the Northern Appalachians Seismic Zone (Adams and Basham, 1989). The causes of seismicity in these zones are thought to be related to late Proterozoic to Paleozoic and Mesozoic rift system reactivation along the Ottawa and St. Lawrence Rivers (Adams and Basham, 1989).

According to Adams and Basham (1989), the WQSZ is divided into two parallel regions of seismicity. The first one trends from the Baskatong Reservoir, about 200 km north of Ottawa, towards Montreal; and, the second one runs along the Ottawa River from Timiskaming to Ottawa, parallel to the first zone, but extending toward the south. The first region, which has more seismic activity, is located over the track of the passage of the North America hotspot 140-120 Ma (Crough, 1981), see Figures 1.1 and 2.2. Therefore, the seismicity of this region is thought to be caused by the thermal rejuvenation of pre-existing faults (Ma and Eaton, 2007). The second region has less seismic activity and is located within the Bonnechere graben.

Adams and Basham (1989, 1991) and Forsyth (1981) suggested that the seismicity along the southwestern edge of the WQSZ is due to Paleozoic rift system reactivation in a state of reverse within the Ottawa-Bonnechere graben. However, the Lamontagne and Ranalli study (2014) show that not all seismicity clusters that are found in this region can be explained by this suggestion.

Nevertheless, there is no direct evidence of spatial relationships between earthquakes and surface features of faults related to rift or Grenville shear zones in the northeastern part of the WQSZ (Forsyth, 1981; Adams and Basham, 1989; 1991; Ma and Eaton, 2007).

Crough (1981) suggested that this zone is located within the Mesozoic track of the Great Meteor Hotspot, and Sykes (1980) and Ma and Atkinson (2006) proposed that the seismicity focus is concentrated along the hotspot track. Based on the Ma and Atkinson (2006) study, the seismicity is controlled by the hotspot track through the thermal rejuvenation of prior faults or the concentration of stress that was created by large differences between the strengths of mafic and felsic mid-crustal rock.

2.3.1 Seismicity Level

The WQSZ has the 2nd highest seismic rate in southeastern Canada. This level of seismicity has significant effects on the seismic hazards in two of the most densely populated cities in southeastern Canada: Ottawa and Montreal (Adams and Halchuk, 2003). The distribution pattern of historical seismic activity in the WQSZ during the time period of 1627 to 2015 (Figure 1.1) suggests that earthquakes are predominantly concentrated along the Ottawa River and the Montreal-Maniwaki axis area. According to recorded seismic data in the GSC catalog, the WQSZ has experienced a few large earthquakes with magnitudes greater than 5.0, in addition to many events with magnitudes of less than 4.0 in the past. Figures 2.4 and 2.5 present the depth distribution of earthquakes that occurred in this time period, and the results show that most of the WQSZ earthquakes occur at depths between 6 and 20 km with some events deeper than 30 km. It should be noted that the depths of older events have not been determined (Halchuk et al., 2015) and about 55% of earthquakes that occurred in the WQSZ have fixed depths in the catalog, which are not

included in analysis of depth distribution and plots in this study. However, in the GSC catalog, 18 km is considered the default value for fixing depths for most of the earthquakes in this region (Basham et al., 1979).

Figure 2.4: Distribution of the hypocentres of earthquakes in the WQSZ (1627-2015). The data used for preparing the map were extracted from Earthquakes Canada, GSC, Earthquake Search (On-line Bulletin), <http://earthquakescanada.nrcan.gc.ca/stndon/NEDB-BNDS/bull-eng.php>, Nat. Res. Can., accessed June 2016, which contained data from 1985 to the end of 2015 and from Seismic Hazard Earthquake Epicentre File (SHEEF2010) used in the fifth generation seismic hazard maps of Canada. Halchuk, S., Allen, T.I., Rogers, G.C., and Adams, J. Geological Survey of Canada, open File 7724, 2015 (<http://geoscan.nrcan.gc.ca/>), which contained data from 1627 to the end of 2010.

Figure 2.5: Depth histogram of earthquakes distribution in the WQSZ (free depths) from 1627 to 2015). The data were extracted from Earthquakes Canada, GSC, Earthquake Search (On-line Bulletin), <http://earthquakescanada.nrcan.gc.ca/stndon/NEDB-BNDS/bull-eng.php>, Nat. Res. Can., accessed June 2016, which contained data from 1985 to the end of 2015 and from Seismic Hazard Earthquake Epicentre File (SHEEF2010) used in the fifth generation seismic hazard maps of Canada. Halchuk, S., Allen, T.I., Rogers, G.C., and Adams, J. Geological Survey of Canada, open File 7724, 2015 (<http://geoscan.nrcan.gc.ca/>), which contained data from 1627 to the end of 2010.

Overall, past studies show that many earthquakes in this seismic zone occur along NW-SE trending thrust faults, corresponding to NE compressional stresses, which are in agreement with the general direction of the eastern North American stress field (Adams and Basham, 1991; Bent et al., 2003). The general hypocentral depths have been estimated to be between 15 and 20 km. (Bent and Perry, 2002). Furthermore, development of the regional depth-phase modelling method (Ma and Atkinson, 2006) has supported these results through the determination of focal depths between 2 and 25 km for earthquakes with $M_N \geq 2.8$.

The goal of this study was further investigation of WQSZ seismicity, including hypocentre locations and focal mechanisms, through the deployment of the USTA stations in addition

to the CNSN stations for two aftershock sequences and all earthquakes with magnitudes of 3.0 or greater ($M_N \geq 3.0$) that have occurred from 2013 to 2015 within this seismic zone.

2.4 HISTORICAL SEISMICITY IN THE WQSZ

Recent paleoseismic studies on large landslides and highly disturbed zones in Champlain Sea sediments in the east Ottawa area have proposed that two geologically destructive prehistoric earthquakes with estimated magnitudes of 7 may have happened in the WQSZ in 4550 and 7060 years B.P. (Aylsworth et al., 2000). In September 1732, an earthquake with a magnitude around M_L 5.8 happened near Montreal which may have caused one possible death and injured many people in addition to causing major damage to houses (Smith 1962; Leblanc 1981).

The area of Timiskaming, in the northern part of the WQSZ, experienced the largest historical earthquake with magnitude of m_b 6.1, M_S 6.0 on November 1, 1935 (Basham et al., 1982). This earthquake, which was caused by reactivation of a rift system (Timiskaming graben), was widely felt throughout much of Eastern Canada and northeastern America and caused property damage in the epicentral region (Bent, 1996a) and a landslide 300 km away from the epicentre (Hodgson, 1936, 1945).

On September 5, 1944, the Cornwall-Massena earthquake with magnitude M_w 5.6 generated much damage (Hodgson, 1945). Using forward modelling of regional waveform recordings, Bent (1996b) determined that this event had a 20 km focal depth (mid-crust) and an oblique thrust mechanism, which is in agreement with the many other event mechanisms in the WQSZ (Adams and Bell, 1991; Zoback, 1992) and also with the regional stress field.

2.4.1 Recent Earthquakes

On October 19, 1990, an earthquake with magnitude m_{blg} 5.0 happened in Mont-Laurier, Quebec, with 23 aftershocks, which was widely felt up to 500 km away from the epicentre and caused minor damage (Lamontagne et al., 1994). In January 2000, the Kipawa earthquake with magnitude m_N 5.2 was recorded near the 1935 earthquake epicentre and was reportedly felt up to 500 km away from the event epicentre (Bent et al., 2002). On April 20, 2002, another earthquake with magnitude M_W 5.0 happened in the Adirondack mountains of New York, near the town of Au Sable Forks (Seeber et al. 2002), which caused damage to engineered structures and properties (Pierre and Lamontagne, 2004).

On June 23, 2010, a M_W 5.2 earthquake occurred in Val-des-Bois, Quebec with a relatively deep mainshock and a large number of aftershocks (Ma and Motazedian, 2012). The results of the studies of Ma and Motazedian (2012) show a northeast dipping thrust mechanism with focal depth of 20-23 km (mid-crustal depth).

The most recent important event in the WQSZ was the M_W 4.6 Ladysmith, Quebec earthquake, which occurred on May 17, 2013. In spite of light damage, it was a relatively large event in the WQSZ (Ma and Audet, 2014). Furthermore, it was very well recorded, due to extensive coverage of the region by the Canadian National Seismograph Network (CNSN) and the US Transportable Array stations (USTA). The mainshock and aftershocks were studied in detail by Bent et al., (2015); and, the results show an oblique thrust mechanism for the mainshock at mid-crustal depth (12-14 km), which is typical in the WQSZ. The aftershock sequence included a M_N 4.1 aftershock and many events with $M_N > 3.0$.

3. DATA SET AND METHODS

3.1 INTRODUCTION

The epicentre, focal depth and focal mechanism of an earthquake are among the main source parameters for earthquake studies, which include seismic hazard analysis and seismotectonic research. The precision and accuracy of the hypocentral location and estimation of the focal mechanism can be affected by several parameters, such as the geometry and design of the seismic network, identification of arrival times and the accuracy of the crustal velocity (Pavlis, 1986; Gomberg et al., 1990). In addition to these factors, the chosen technique for the hypocentral determination also plays a significant role in the accuracy of the hypocentral location assessment. Various results with various accuracies can be obtained from different methods.

In this study, the relocations were done based on standard travel time inversion, the double-difference (DD) algorithm and joint hypocenter determination (JHD) method. The DD algorithm using the hypoDD program (Waldhauser and Ellsworth, 2000) was used to provide the hypocentral location for the aftershock sequences of both the 2010 Val-des-Bois (Set #1, see Section 1.3) and 2013 Ladysmith (Set #2, see Section 1.3) earthquakes. This technique identifies clusters of events and determines relative relocations. It is particularly useful when the events have close hypocentral distances. In addition, the JHD method through the VELEST program (Kissling, 1995) was used to simultaneously locate events and develop a one dimensional (1D) velocity model.

Travel times using the DAN program (Nanometrics Inc.) were used to determine the hypocentres of 18 events (Set #3, see Section 1.3). The polarities of the first motions

through the FOCMEC program (Snoke et al., 1984) were used to estimate focal mechanisms of 30 events including the events of Set #3 and the Ladysmith mainshock.

Brief descriptions of the DD algorithm, hypoDD program, JHD method, the VELEST program, standard travel time inversion method, and DAN and FOCMEC programs are provided in the following sections.

3.2 DOUBLE-DIFFERENCE RELOCATION ALGORITHM

The DD technique locates earthquakes based on Geiger's method, which is an iterative least-squares technique for earthquake location (Geiger, 1912), and uses the differences between the observed, and calculated pairs of travel time for primary (P) and secondary (S) waves. The DD algorithm is utilized through the use of the hypoDD computer program, (Waldhauser and Ellsworth, 2000), which discerns and corrects data-model residuals of travel time accordingly and can improve the accuracy of earthquake hypocentre location.

The DD technique uses a number of events with close hypocentres. When the hypocentral distance between two events is small compared to their distance from a seismic station and the scale length of velocity heterogeneity, they have similar seismic ray paths. In this case, the travel time difference between paired events recorded at the same station is related to the spatial differences of each event.

This technique minimizes the double-difference residuals for paired events at a station; and, as a result, systematic travel time errors are corrected, although random errors in the original locations remain. The methodology for this algorithm has been explained in detail by Waldhauser and Ellsworth (2000).

Relocation of earthquakes with hypoDD software consists of two main steps. First, the phase data of the catalog are analyzed, and the events are grouped into pairs and connected to neighbours using the ph2dt program. In the second step, DD hypocentre locations are determined with the hypoDD program using ph2dt output.

3.2.1 ph2dt Program

The Ph2dt program uses cataloged P- and S-phase data for each event pair and their travel time differences at a single station to provide a link between neighbouring event pairs. Consequently, a cluster or network of links between paired events are defined. ph2dt applies predefined parameters in order to create event pairs, links, networks of connected event pairs, and clusters. Therefore, the distance between paired events needs to be minimized, while a defined chain of event pairs, which creates a cluster, needs to be as large as possible in order to obtain the best results.

The input file for this program includes minimum pick weight, maximum distance between event pair and station, maximum hypocentral separation between event pairs (MAXSEP), maximum neighbours per event, minimum links in a neighbour, minimum observations and maximum observations. The values for many of these parameters are default values according to Waldhauser (2001). All of these items, except MAXSEP, were kept constant through all trials in this study.

There is a problem when the DD calculations exceed the array capacities of hypoDD, or the computer memory. In order to avoid this problem, a limitation on the number of links per event pair was defined by the Minimum number of links (MINOBS) and maximum number of links (MAXOBS). The MINOBS value was set to 1 to cover all recorded phase pairs, and the MAXOBS value was set at 100 which, was the same as the number of

stations. Another significant option, which may overcome this issue of excess calculations, is the limitation of the number of neighbours; therefore, an upper limit of neighbours for each event (MAXNGH), was set at 100.

MAXSEP is a certain radius of an event pair within which another event pair can fall and create a neighbour. The MAXSEP was a parameter that was varied in this study. The results demonstrate that the most accurate scale to set for event pairs, neighbours and clusters was conveyed by a MAXSEP set at a value of five kilometres. The output from ph2dt was fed into hypoDD as input files.

3.2.2 hypoDD Program

The hypoDD program uses differential time information, forms clusters from paired events, and calculates DD earthquake locations. A cluster consists of a few series of paired events that contain strongly linked neighbours within a predefined range of criteria. After a few trials, these key parameters were defined as described in the following paragraphs.

The maximum distance between the cluster center and the stations was set to 200 km. The minimum number of catalog links for each event pair that was needed to establish a cluster was typically set to 8 to cover all degrees of freedom. Singular value decomposition (SVD) was used instead of the conjugate gradients method (LSQR), because there was a small system of events in this study and, according to Waldhauser (2001), SVD is beneficial for assessment of the small system behaviour, providing information about the hypocentral parameters and defining least square errors by calculating the appropriate covariance.

In order to decrease the DD residuals, the process of relocation needed to be repeated. The number of iterations was set to 2, 3, 4 and 5 for each trial; and, the determined weights for

the catalog P- and S-wave data were set to 1 and 0.5, respectively. The upper limit of distance between two events in an event pair (WDCT) for the catalog data was set to 5 km. Since WDCT is similar to MAXSEP, the value of WDCT was considered equal to that of the MAXSEP. Other input data to hypoDD were a defined velocity model and an identification (ID).

In order to choose the appropriate parameter values, several trials were done, and the results were applied to the Western Quebec Seismic Zone (WQSZ), as reflected in the following two subsections.

3.2.3 Double-Difference Technique in the WQSZ

The data set for this study was a compilation of two aftershock sequences from the 2010 Val-des-Bois (Set #1) and 2013 Ladysmith (Set #2) earthquakes. The arrival time data were taken from the pick files in the GSC (Geological Survey of Canada) database; and, the arrival times of the USTA (US Transportable Array) stations from 2013 through 2015 were added.

Since the MAXSEP value controls the number of relocated events, it should be considered small in comparison to the distance between the event and station (Waldhauser, 2001). By increasing the MAXSEP value, more event pairs are generated; consequently, the number of relocated events and errors are increased. Therefore, a series of trials were done based on three different values of MAXSEP: 2, 5 and 10 km. A MAXSEP value of 10 km was used based on the recommendation by Waldhauser (2001).

In the Val-des-Bois earthquake, the largest obtained cluster included 28 relocated events for a MAXSEP of 10 km. When a MAXSEP of 5 km was applied, the largest resulting

cluster revealed 21 relocated events. In both cases, a relatively large value of errors was found for the relocations. However, only 9 events were relocated when a MAXSEP of 2 km was used. In the Ladysmith earthquake, the largest obtained clusters were 29, 27 and 16 relocated events for MAXSEP values of 10, 5 and 2 km, respectively, with decreasing errors.

In light of these results, the MAXSEP value of 10 km was not used, due to the large values of obtained errors. The most accurate value to set up event pairs, neighbours and clusters was obtained by using a MAXSEP value of 5 km which provides an appropriate number of relocated events with a relatively small value for the error at the point when all components are evaluated.

According to Waldhauser (2001), the largest contribution to the relocations occurs in the earliest few iterations, so the studied events were relocated by using two iterations (NITER=2). The relocation process was then continued for 3, 4 and 5 iterations. The results obtained for NITER = 3, 4 and 5 for both aftershock sequences are given in Appendix A.

3.2.4 Different Velocity Models used in the hypoDD Program

Travel times are calculated in the hypoDD program through the layered velocity model for phases recorded at the stations. Five different velocity models were applied in this study. This program was run for the Brune and Dorman (1963), Motazedian et al., (2013), Motazedian and Ma (2014) and Darbyshire et al., (2007) velocity models, as outlined in Table 3.1. The fifth velocity model (V5) was obtained from running the VELEST program (Kissling, 1995) and used as outlined in Table 3.2. The procedure of using the VELEST program is briefly discussed in section 3.3. All the shear wave velocity (V_s) models are 1D models; brief descriptions are given in the following points:

- Velocity model 1 (V1). Brune and Dorman (1963) derived a layered model of the crust and upper mantle using curve-fitting of Canadian shield phase velocity data (between Resolute and Ottawa, Resolute and Palisades, and Resolute and Halifax) in the period ranges of 20 to 90 seconds and 22 to 60 seconds for Rayleigh waves and Love waves, respectively. An inversion least-squares method was applied. They combined the surface wave dispersion method with travel time data and provided reliable information on the distribution of shear wave velocity in a 35.2 km thick three-layered crust with increasing velocity up to 3.85 km/sec, in the upper mantle with a velocity of 4.72 km/sec down to a depth of 115 km, and the low velocity channel with a velocity of about 4.5 km/sec down to a depth of 315 km depth.
- Velocity model 2 (V2). Motazedian et al., (2013) obtained 14 crustal velocity models using Rayleigh-Wave dispersion data in the period range of 5 to 22 seconds around the epicentre of the 23 June 2010 Val-des-Bois earthquake in Quebec. They formed one model for the north side of the Ottawa-Bonnechere graben and another model for the south side, which had average velocities slower than the north side.
- Velocity model 3 (V3). Motazedian and Ma (2014) obtained shear wave velocities using the dispersion of Rg, which are high-frequency Rayleigh waves (the short period Rg waves propagate as guided waves through crust) generated by an M_N 3.0 earthquake in Georgian Bay in 2007, a mining induced event Sudbury in 2005, and a large earthquake near Thunder Bay in 2008 (southern Ontario). They found a common feature of in all studied areas a 0.5 km thick layer with low velocity.

-Velocity model 4 (V4). Darbyshire et al., (2007) presented a shear wave velocity model of the lithosphere and upper mantle beneath the Superior Province (northern and eastern Ontario) using the teleseismic Rayleigh waves dispersion method in the period range of 25 to 170 seconds and analysis of seismic network data down to a depth of 300 km. They found a varied high-velocity mantle lid caused by seismic anisotropy. Using receiver function analysis, they introduced thicknesses about 34 to 44 km of the crust and 100 to 240 km of the lithosphere through large parts of Ontario.

There are lateral variations in shear wave velocities due to the heterogeneity in natural soils and their lithology and structure variations. The variations in the velocities are evidence of variation in the crustal structure and are related to their geographical locations. Lateral variations in shear wave velocity model are needed to analyze stress deformation in order to achieve seismic design. However, 1D shear wave velocity models do not show the heterogeneity of the velocities in nature.

Table 3.1: Four velocity models used in the hypoDD program

No. of layer	V1 Brune and Dorman (1963) model		V2 Motazedian et al.,(2013) model		V3 Motazedian and Ma (2014) model		V4 Darbyshire et al., (2007) model	
	h (km)	Vp (km/s)	h (km)	Vp (km/s)	h (km)	Vp (km/s)	h (km)	Vp (km/s)
1	0.0	5.64	2.0	6.20	2.0	5.54	0.0	6.41
2	6.0	6.15	6.0	6.16	6.0	5.61	15.0	6.41
3	16.0	6.60	10.0	6.11	10.0	5.99	35.0	6.93
4	36.0	8.10	14.0	6.18	14.0	6.20	45.0	7.79
5			17.0	6.27	17.0	6.51		
6			21.0	6.46	21.0	6.67		
7			24.0	6.41	24.0	6.70		
8			28.0	6.33	28.0	6.50		
9			33.0	6.33	34.0	6.58		
10			40.0	6.83	40.0	7.19		

h: depths to the top of layer (km)

Table 3.2: Velocity models resulting from the VELEST program and used in hypoDD program (Kissling, 1995)

No. of layer	V5 (resulted from VELEST program)			
	<u>Val-des-Bois earthquake</u>		<u>Ladysmith earthquake</u>	
	h (km)	Vp (km/s)	h (km)	Vp (km/s)
1	-1	5.64	-1	5.70
2	0	5.92	0	5.70
3	6	6.46	6	6.02
4	16	6.46	16	6.25
5	36	8.21	36	8.08

h: depth to the top of layer (km)

3.3 JOINT HYPOCENTRE DETERMINATION METHOD

The relocation of two aftershock sequences was performed using a 1D velocity model obtained from the simultaneous inversion and coupled hypocentre-velocity model through the VELEST program (Version 3.1) (Kissling et al., 1994; Kissling, 1995).

This program simultaneously estimates the location of earthquakes and calculates the 1D (layered) velocity model with station corrections and performs the joint hypocenter determination (JHD). The calculation of this model requires an initial velocity model and several trials and errors with various combinations of control parameters to select the proper factors. In this model, rays are traced from the source to the receiver; and, the direct, refracted, and reflected rays are computed using the 1D model.

In this study, the general procedure and default values of parameters suggested by Kissling (1995) was followed; and, the Brune and Dorman model (1963) was selected as the initial velocity model. The coordinates of seismic stations and, local earthquake data, such as hypocentre and magnitude, were obtained from the database; and, travel times, including phase type and phase weight, were determined from the data.

The main output file of this program contains the new velocity model and provides details about the procedure and intermediate steps of the calculation for each iteration. The final proper control parameters can be obtained from these results through several runs of the VELEST program. The negative value for depths in Table 3.2 is due to calculation relative to sea level (not to station elevations), which shows the upper interface of the velocity layer. For a more detailed explanation of the process of this program, see the VELEST user's guide (Kissling, 1995).

The relocated hypocentres obtained from VELEST were compared with those obtained from hypoDD using the velocity model derived from VELEST in Chapters 4 and 5.

The final obtained velocity models for both aftershock sequences of the Val-des-Bois (Set #1) and Ladysmith (Set #2) earthquakes were compared with initial velocity models and are shown in Figure 3.1. The calculated velocity model for the Val-des-Bois aftershocks was higher than the initial model, except a decrease at the depth range of 16 to 36 km. The final velocity model for the Ladysmith aftershocks was lower than the initial model, except of a trivial increase for the first 6 km of the depth.

Figure 3.1: Final computed velocity model (continuous line) derived from initial P-wave velocity model (dashed line) for the aftershock sequences of the Val-des-Bois (a) and Ladysmith (b) earthquakes.

3.4 STANDARD TRAVEL TIME INVERSION METHOD

The relocations of 18 events (Set #3) were done based on travel time through the DAN program which was provided by Nanometrics Inc. (<http://www.nanometrics.ca/seismology>) for the Geological Survey of Canada (GSC) with some in-house modifications.

3.4.1 Data Setting

In this study, the data from the USTA were added to data from the Canadian National Seismograph Network (CNSN); and, it was found that some of the 96 seismic stations recorded 18 earthquakes with magnitudes greater than 3.0 ($M_N \geq 3.0$) from January 2013 through July 2015 in and near the WQSZ. In the majority of the studied events, 25 or more stations were used in the depth estimation process (Figure 3.2).

Figure 3.2: Number of used stations for depth estimation of each event, the blue line shows the average number of stations

A list of all studied events and their pick files were extracted from the Canadian National Earthquake Database available from the GSC. Each pick file contained phase information and solution records, solution error record, magnitude record and comments.

There were five common events in this set (Set #3) and Set #2 - the aftershock sequence of the Ladysmith earthquake, including the M_w 4.6 Ladysmith earthquake, 18 km NE from Shawville, QC on 17th of May 2013, which was the strongest event in this list (20130517-A), and events 20130517-B, 20130517-C, 20130530 and 20130630 (Table 4.5).

3.4.2 Data Analysis in the DAN Program

A combination of two sets of the CNSN and the USTA waveforms data were used to pick the travel times of the P- and S-waves and to calculate the focal depths for all events. The focal depths were calculated through the DAN program using the Brune and Dorman velocity model (1963) which is usually used for the estimation of earthquake locations in Eastern Canada.

Pn, Pg (Sn, Sg) (Pn and Sn are refracted waves that propagate the uppermost mantle) (Pg and Sg are direct crustal phases) were properly identified regarding the distance between the station and the epicentre. Pg and Sg represent the close distances, and Pn and Sn the further distances. It is worth noting that unclear seismograms at distances far from the earthquake epicentre were ignored. The compressional (C) and dilatational (D) waves of the first P-wave arrival were identified and were used in the focal mechanism determination (Chapter 6).

The important factors that define the applied weights of the phases are the accuracy of the arrival times, the time residual and the epicentral distances. The weight phases were

assigned only when the residual was less than one second in the pick files. A weight of four was assigned, if the waveform was very clear; a weight of one was applied if wave was not very clear; and a weight of zero was used, if the error was more than one second. Using the free depth option, the focal depths were then calculated. Bandpass filtering of 3 Hz and 10 Hz were applied for the estimation of location to remove noises. The program output contained seismic parameters, such as the location of hypocenter and station parameters, such as take-off angle and azimuth.

In the next step, the process was repeated choosing the fixed depth at 18 km. The solutions and errors with free depth and fixed depth options were compared with each other and with those of the original pick file. The focal depth with the least error was chosen as an acceptable solution.

3.5 FOCMEC PROGRAM

A focal mechanism solution is one of the potential outcomes of earthquake wave analysis.

The characteristics of forces that create the earthquakes are determined by a focal mechanism solution. Determination of an appropriate focal mechanism solution in some methods strongly depends on the geographical distribution of the seismic stations around the epicentre of an earthquake.

There are several important factors about regional tectonic stresses that can be provided by the focal mechanism, such as the orientation and magnitude of the pressure (P) and tension (T) axes.

The focal mechanism solution contains two nodal planes (perpendicular to each other) that need to be compared with geological structures; one of the planes is assumed the fault surface and the other one is the auxiliary plane. Therefore, information such as the location and trend of aftershocks in addition to a precise interpretation of the graphic sketch of the focal mechanism solution (beach-ball diagram) are necessary to determine the orientation and slip direction of the fault plane and the type of the fault. This is one of the reasons for relocating the hypocentres of the two aftershock sequences in Set #1 and Set #2.

The focal mechanism solution contains the orientation of the fault and its relevant slip vector. Figure 3.3 shows the dip (the angle of the fault from the horizontal plane, δ) and strike (ϕ_f) of the fault plane and the rake of the hanging-wall slip vector (λ) defined by the focal mechanism solution.

Figure 3.3: Image of fault geometry. Earthquake source parameters resulted from the focal mechanism solution are displayed as: d , δ , ϕ_f and λ (d : slip vector; δ : dip angle; ϕ_f : strike and λ : rake angle) (Stein and Wysession, 2003, with permission).

3.5.1 Process of the FOCMEC Program

The input data used for the FOCMEC program are azimuths, take-off angles and polarities. After running the FOCMEC program, a summary of the acceptable mechanism solutions is given as result. These solutions are selected based on the definition of the input parameters (azimuths, take-off angles, and polarities), restriction on the allowed P polarity errors, and increment for the trend and plunge of the B axis (the intermediate stress axis or intersection of the nodal planes) and the angle of the A axis (axis of a double couple point source).

Since there are two possible solutions for planes that qualify for these criteria, two sets of dip, strike and rake values are obtained by a single solution; consequently, two nodal planes (fault plane and auxiliary plane) are represented for every solution. Trend and plunge determination of the P and T axes are different parameters of the same focal mechanism solution. The P axis specifies the maximum compression direction, and the T axis defines the maximum tension direction.

3.5.2 Method

Reading the P-wave first motion directions as recorded by seismographs is an input parameter required for determining focal mechanisms. Reading the seismogram from each station enables us to evaluate whether the first motion was a down or up movement. These seismograph stations included both CNSN and USTA data. In order to get the true first motion direction, attempts were made to read the unfiltered data, because there was the possibility of losing the true first motion during reading filtered data, due to greater attenuation of high frequencies than low frequencies. Nevertheless, the range of frequencies for small events persuaded us to filter some of the seismograms. The data had

been highpass-filtered (highpass is an infinite impulse response filter) with corner frequencies at 1 Hz through the Seismic Analysis Code (SAC) (Tapley and Tull, 1991). All filters were two-pole Butterworth filters. It was also necessary to know the ray path azimuth and its take-off angle for each station.

The procedure that was followed for determining the focal mechanism in the FOCMEC program initially started with a zero P polarity error and increments of 5 degrees for the B trend, the B plunge and the A angle. The search increment was reduced to 2 degrees, if no solution was found. The procedure was repeated with 5 degree increments and one allowed P polarity error. The alternately downtrend interval and uptrend allowed the P polarity system to be iterated in order to obtain at least one solution.

The polarities that were used to obtain the fault plane solutions are presented in Appendix B (Tables B.1 to B.30). Compressional and dilatational polarities are marked by C and D, respectively. Compression and dilatation for emergent P polarities are specified by + and −, respectively. Polarities that could not be resolved with certainty were ignored.

Figure 3.4 displays the relation between the orientation of the fault plane and the first motion. In order to clarify where the first motion was picked, examples of portions of the seismograms for one of the events, from which polarity data were read, are included in Appendix B (Figures B.1 to B.17). The focal mechanism solutions plotted in terms of both stress axes and P nodal planes are also presented in Appendix B (Figures B.18 to B.119). The seismograms have been modified to show only the 4 seconds of recording prior to the first arrival of the P-wave motion. The evaluations of azimuth and strike were in terms of degrees clockwise from north, of take-off angles from an imaginary vertical line, and of

dip angles from the plane of the horizontal. Rake is also known as the slip angle. Rake angles for pure normal and pure thrust faults are -90° (or 270°) and 90° , respectively. A rake of 180° defines pure right lateral strike-slip and 0° shows left lateral strike-slip faults.

Figure 3.4: Relation between the first motions and fault plane orientation, (Stein and Wyssession, 2003, with permission).

4. EPICENTRE RELOCATION

This chapter is divided into three parts and describes the applied procedure for estimation of the relocated epicentres of earthquakes when the US Transportable Array (USTA) data were added to the Canadian National Seismic Network (CNSN) data.

In the first and second parts, the hypocentres of the two aftershocks sequences of the 2010 Val-des-Bois (Set #1) and 2013 Ladysmith earthquakes (Set #2) were relocated using the double-difference (DD) method through the hypoDD program and then compared with the results obtained with the joint hypocentre determination (JHD) method through the VELEST program.

In the third part, the hypocentres were obtained for 18 earthquakes (Set #3) with the standard travel time method through the DAN program. In each part, two data sets, one from the CNSN and the other from the USTA, were combined; and, the results were compared.

It should be noted that the hypocentre solutions were determined using the hypoDD and VELEST programs; however, it was decided to discuss epicentres in this chapter and the focal depths in the next chapter, for consistency and clarity.

4.1 DOUBLE-DIFFERENCE ANALYSIS OF THE VAL-DES-BOIS AFTERSHOCKS USING ONLY THE CNSN DATA

The Val-des-Bois earthquake with a moment magnitude (M_w) of 5.2 and a focal depth of about 21 km occurred on June 23, 2010. This event occurred on a northwest striking thrust fault about 60 km north-northeast of Ottawa (Ma and Motazedian, 2012).

It should be mentioned that for the Val-des-Bois event, only the late part of the aftershock sequence (during the period of 2013 to 2015, when the USTA was deployed) is included.

Set #1 had a total of 45 recorded events for the Val-des-Bois earthquake with magnitudes (M_N) ranging between 0.4 and 3.4, as outlined in Table 4.1. The distribution of these aftershocks is shown in Figure 4.1.

Table 4.1: Summary of the studied late aftershock sequences of the Val-des-Bois earthquake occurring during 2013-2015. *Focal depth has been calculated using RDPM, the “g” means the depth was fixed, (Canadian Seismic Activity-Provisional Summary-Observatory Crescent and Pacific Geoscience Centre, GSC, Canadian National Earthquakes Database (CNED)).

No.	Date	Time (UT)	Lat (°N)	Long (°W)	Depth (km)	Mag (M_N)	Region
1	2013/03/10	14:54:37	45.90	75.50	18.0g	1.7	8 km E from Val-des-Bois, QC
2	2013/03/16	19:56:48	45.93	75.64	18.0g	1.0	3 km NW from Val-des-Bois, QC
3	2013/03/22	05:06:30	45.86	75.50	18.0g	0.4	10 km SE from Val-des-Bois, QC
4	2013/06/02	07:02:41	46.03	75.38	18.0g	1.3	22 km NE from Val-des-Bois, QC
5	2013/06/13	21:11:30	45.86	75.50	20.4	1.5	10 km SE from Val-des-Bois, QC
6	2013/06/17	04:48:39	45.85	75.55	18.0g	1.0	8 km SE from Val-des-Bois, QC
7	2013/06/21	10:14:38	45.87	75.53	18.0g	1.2	8 km SE from Val-des-Bois, QC
8	2013/07/27	22:47:09	45.87	75.49	18.0g	2.3	10 km SE from Val-des-Bois, QC
9	2013/09/09	18:00:25	45.86	75.54	18.0g	1.7	8 km SE from Val-des-Bois, QC
10	2013/09/16	01:42:14	45.97	75.50	18.0g	1.4	10 km NE from Val-des-Bois, QC
11	2013/10/17	08:38:33	45.87	75.50	18.0g	1.5	9 km SE from Val-des-Bois, QC
12	2013/10/27	06:27:24	45.89	75.52	18.0g	1.5	6 km SE from Val-des-Bois, QC
13	2013/11/20	05:57:23	45.87	75.48	18.0g	1.7	11 km SE from Val-des-Bois, QC
14	2013/11/24	22:09:35	45.89	75.47	18.0g	1.0	10 km E from Val-des-Bois, QC
15	2013/12/16	10:50:52	46.15	75.41	18.0g	1.2	30 km NE from Val-des-Bois, QC
16	2014/01/24	13:38:00	45.87	75.52	18.0g	2.0	8 km SE from Val-des-Bois, QC
17	2014/03/05	06:31:28	45.72	75.36	18.0g	-0.5ML	16 km N from Buckingham, QC
18	2014/03/05	20:26:09	45.94	75.40	18.0g	0.9	16 km E from Val-des-Bois, QC
19	2014/03/28	21:15:17	46.04	75.30	18.0g	1.9	27 km NE from Val-des-Bois, QC
20	2014/04/21	03:47:40	45.86	75.48	18.0g	0.9	11 km SE from Val-des-Bois, QC

21	2014/12/03	04:10:38	45.85	75.48	18.0g	0.7	12 km SE from Val-des-Bois, QC
22	2015/01/04	14:54:08	46.05	75.40	18.0g	1.3	22 km NE from Val-des-Bois, QC
23	2015/01/24	03:59:45	46.12	75.41	18.0g	2.1	27 km NE from Val-des-Bois, QC
24	2015/01/27	00:53:58	45.87	75.45	18.0g	1.1	13 km SE from Val-des-Bois, QC
25	2015/02/11	10:17:43	45.86	75.46	18.0g	1.2	13 km SE from Val-des-Bois, QC
26	2015/03/02	15:56:08	45.92	75.42	18.0g	1.3	14 km E from Val-des-Bois, QC
27	2015/03/12	02:22:42	45.86	75.42	18.0g	-0.2ML	16 km SE from Val-des-Bois, QC
28	2015/03/12	14:12:58	45.88	75.50	18.0g	1.8	9 km SE from Val-des-Bois, QC
29	2015/03/21	09:33:26	45.96	75.65	18.0g	1.0	6 km NW from Val-des-Bois, QC
30	2015/05/04	17:30:29	45.86	75.48	18.0g	1.6	12 km SE from Val-des-Bois, QC
31	2015/05/08	01:15:01	45.88	75.51	18.0g	1.1	8 km SE from Val-des-Bois, QC
32	2015/05/14	09:17:38	45.99	75.57	18.0g	1.0	9 km N from Val-des-Bois, QC
33	2015/06/16	00:49:04	45.90	75.43	18.0g	1.1	13 km E from Val-des-Bois, QC
34	2015/06/20	03:56:03	45.96	75.67	18.0g	0.9	7 km NW from Val-des-Bois, QC
35	2015/07/24	08:03:46	46.14	75.45	18.0g	2.0	28 km NE from Val-des-Bois, QC
36	2015/08/01	01:16:16	45.90	75.47	18.0g	1.5	10 km E from Val-des-Bois, QC
37	2015/08/05	07:37:51	45.89	75.59	*15.0g	3.4	3 km S from Val-des-Bois, QC. Felt
38	2015/08/05	07:56:05	45.89	75.57	18.0g	2.7	4 km SE from Val-des-Bois, QC. Aftershock. Felt
39	2015/08/05	17:30:39	45.88	75.58	18.0g	1.7	5 km S from Val-des-Bois, QC. Aftershock
40	2015/08/08	09:08:29	45.89	75.56	18.0g	2.5	4 km SE from Val-des-Bois, QC. Felt
41	2015/08/14	08:53:03	45.90	75.46	18.0g	1.1	11 km E from Val-des-Bois, QC
42	2015/08/30	20:27:39	46.06	75.62	18.0g	3.2	17 km N from Val-des-Bois, QC. Felt
43	2015/10/04	09:12:36	45.90	75.20	18.0g	1.1	23 km NW from Saint-Andre-Avellin, QC
44	2015/10/04	09:12:10	45.91	75.21	18.0g	-0.6ML	24 km NW from Saint-Andre-Avellin, QC
45	2015/10/24	13:20:29	46.07	75.34	18.0g	1.0	26 km NE from Val-des-Bois, QC

Figure 4.1: Distribution of the 45 late-aftershock sequences of the 2010 Val-des-Bois earthquake represented by empty circles. The sizes of the circles are proportional to the magnitude.

In this study, 45 late aftershocks of the Val-des-Bois earthquake were relocated using the hypoDD program and five velocity models described in Section 3.2. The hypoDD program was run using only the CNSN data. The resulting relocated hypocentres using velocity

model 1 (V1) are presented in Table 4.2. The clustered distributions of the relocated epicentres, using all five different velocity models, and those of the GSC catalog are presented in Figure 4.2.

Table 4.2: Relocated hypocentres of the Val-des-Bois earthquake aftershocks using only the CNSN data, calculated from the hypoDD program using MAXSEP = 5, NITER = 2 and V1. The negative longitude values indicate degrees west.

ID	Lat	Long	Yr	Mo	Dy	Hr	Min	Sec	Mag	Depth	
										Catalog	hypoDD
1	45.893766	-75.511108	2013	3	10	14	54	37.610	1.7	18.00	17.78
5	45.860860	-75.489185	2013	6	13	21	11	30.160	1.5	20.40	19.98
8	45.874329	-75.498413	2013	7	27	22	47	9.360	2.3	18.00	18.73
11	45.872795	-75.499007	2013	10	17	8	38	33.740	1.5	18.00	18.41
12	45.896187	-75.524121	2013	10	27	6	27	24.830	1.5	18.00	17.44
13	45.867253	-75.473519	2013	11	20	5	57	23.780	1.7	18.00	17.82
16	45.881295	-75.516309	2014	1	24	13	38	0.560	2.0	18.00	17.54
20	45.865499	-75.471126	2014	4	21	3	47	40.780	0.9	18.00	16.91
24	45.860457	-75.450081	2015	1	27	0	53	58.980	1.1	18.00	17.79
25	45.876314	-75.438485	2015	2	11	10	17	43.370	1.2	18.00	17.48
28	45.879093	-75.503206	2015	3	12	14	12	58.300	1.8	18.00	17.48
30	45.855306	-75.481925	2015	5	4	17	30	29.080	1.6	18.00	17.35
31	45.877185	-75.524105	2015	5	8	1	15	1.660	1.1	18.00	19.20
36	45.902271	-75.455119	2015	8	1	1	16	16.500	1.5	18.00	18.09
41	45.895858	-75.451213	2015	8	14	8	53	3.500	1.1	18.00	17.58

Figure 4.2: Clustered epicentral distribution of Val-des-Bois aftershocks using only the CNSN data. The blue circles show the GSC catalog epicentres. The white stars, green-yellow diamonds, black plus symbols, pink triangles, and light brown squares represent the relocated epicentres using velocity models V1, V2, V3, V4 and V5, respectively. The sizes of the symbols are proportional to the magnitude. The direction of epicentre movement of two events are shown by arrows (some of relocated events have lost their link and were removed from clusters).

The relocated epicentres obtained from all velocity models showed northwest-southeast seismicity trends, which are compatible with the seismicity pattern in this region. However, locations using the V1 and V5 had the most similarity with those using the GSC catalog dataset, in terms of maximum and minimum epicentral displacement. The reason for this

similarity is V1 is usually used in the determination of the seismic parameters in the GSC catalog (as a standard model for this region). V1 was also selected as the initial model in the VELEST program, which provided V5.

Figure 4.3 shows the distance, regardless of direction, of the relocated epicentres for the Val-des-Bois aftershocks using all five velocity models and those of the GSC catalog. Event 36 in V3 and event 37 in V4 exhibited large differences between the relocated and original epicentres in the catalog (about 8.0 and 5.3 km, respectively). However, these same two events showed smaller differences in V5. These large differences may have been related to inaccuracy in reading the arrival time, the number of available phases or the applied velocity models, which are some factors that control the accuracy of hypocentral locations. Event 5 in V1, V2 and V5 showed small differences between the relocated and original epicentres in the catalog, i.e. about 1.0 km.

Figure 4.3: Epicentral distance between catalog and relocated Val-des-Bois aftershocks using only the CNSN data and five different velocity models. The distances between relocated epicentres obtained from V1, V2, V3, V4 and V5 and epicentres in catalog are shown by squares, diamonds, upward triangles, downward triangles and oblique crosses, respectively. Standard deviations of the average distances are shown by vertical black lines.

4.1.1 Comparison of the Relocated Epicentres of the Val-des-Bois Aftershocks through VELEST and hypoDD programs using only CNSN Data

The events in Set#1 were relocated using the JHD method through the VELEST program using only the CNSN data. The resulting relocated epicentres were compared with the results obtained by the DD method through the hypoDD program using V5, as shown in Figure 4.4. It should be noted that V5 was obtained from the VELEST program. The comparison of the results using the same velocity model, but various methods showed almost the same seismicity trend pattern. However, the value of uncertainties decreased when the JHD method was applied.

Figure 4.4: Comparison of the relocated epicentres of the Val-des-Bois aftershocks obtained by different methods but the same models using only CNSN data. The results obtained by hypoDD using V5 are represented by the dark triangles, the results obtained by the VELEST are represented by the red crosses, and the epicentres in the GSC catalog are represented by the blue circles. Uncertainties come from the output files of programs and are shown by the vertical and horizontal lines.

4.2 DOUBLE-DIFFERENCE ANALYSIS OF THE VAL-DES-BOIS AFTERSHOCKS USING CNSN AND USTA DATA

In the next step, the aftershock sequence of the Val-des-Bois earthquake was relocated using both CNSN and USTA data sets in the hypoDD program and the five velocity models. Figures A.1 – A.18 and Tables A.1 – A.17 in Appendix A display the relocated hypocentres for the Val-des-Bois aftershocks. The following results were obtained using 5 km for the maximum event separation (MAXSEP).

The clustered distributions of the relocated Val-des-Bois aftershock epicentres obtained from the hypoDD using all five different velocity models, and those of the GSC catalog are presented in Figure 4.5.

The relocated epicentres obtained from the different velocity models showed the same seismicity trend along the northwest-southeast direction, which is compatible with the seismicity pattern in this region. However, locations using velocity models V1, V2 and V5 exhibited the most similarity with those from the GSC catalog data set, in terms of maximum and minimum epicentral displacement. In addition to the similarities in locations using V1 and V5, which are also in common with the results obtained from using only the CNSN data, locations using V2 had similarity with those using the GSC catalog data set when the USTA data were included. This may have been due to the impact of more travel time data in the determination of epicentres in V2. Relocated epicentres showed a different seismicity pattern when V4 was used, which may have been due to higher values of the velocities than those in the other models.

Figure 4.5: Clustered epicentral distribution of Val-des-Bois aftershocks using both CNSN and USTA data. The blue circles show the GSC catalog epicentres. The white stars, green-yellow diamonds, black plus symbols, pink triangles, and light brown squares represent the relocated epicentres using velocity models V1, V2, V3, V4 and V5, respectively. The sizes of the symbols are proportional to the magnitude. The directions of epicentre movement of six events are shown by arrows.

To have a better visual than the clustered Figure 4.5, the epicentral distribution of some of the biggest events of the Set #1 is presented in Figure 4.6.

Figure 4.6: Epicentral distribution of some of the biggest Val-des-Bois aftershocks using both CNSN and USTA data. The blue circles show the GSC catalog epicentres, and the relocated epicentres using velocity models V1, V2, V3, V4 and V5 are displayed by the white stars, green-yellow diamonds, black plus symbols, pink triangles and light brown squares, respectively. The sizes of the symbols are proportional to the magnitude. The directions of epicentre movement of four events are shown by arrows.

Figure 4.7 shows the distance, regardless of direction, between the relocated epicentres for the Val-des-Bois aftershocks using all five velocity models and those of the GSC catalog. Events 37 and 9 exhibited large differences between the relocated epicentres and the original epicentres in the catalog about 7.1 and 3.5 km, respectively. These large differences may have been related to probable inaccuracy in reading the arrival time, the number of available phases or the applied velocity models, which are some of the factors

that control the accuracy of hypocentral locations. Events 5 and 13 showed small differences between relocated and original epicentres about 0.2 and 0.6 km, respectively.

Figure 4.7: Epicentral distance between catalog and relocated Val-des-Bois aftershocks using both CNSN and USTA data and five different velocity models. The distances between relocated epicentres obtained from velocity model V1, V2, V3, V4 and V5 and epicentres in the GSC catalog are shown by squares, diamonds, upward triangles, downward triangles and oblique crosses, respectively. Standard deviations of the average distances are shown by vertical lines.

The average uncertainties in epicentral differences between the relocated epicentres and those in the GSC catalog for each velocity model are shown in Figure 4.8(a). It seems that events 9 and 37 generally had the most uncertainties. Regardless of these two events, V1 and V5 provided lower uncertainties. This suggests that the more accurate epicentres can be determined using V1 and V5.

The average differences between the relocated epicentres and the ones in the GSC catalog using only the CNSN data and both CNSN and USTA data are presented in Figure 4.8(b). The uncertainties are also displayed in this figure. The values of the epicentral distance uncertainties measurement indicate relatively higher uncertainties in locations of events when only the CNSN data were used compared to using both CNSN and USTA data.

Figure 4.8: Epicentral distances between catalog data and relocated Val-des-Bois aftershocks using five velocity models: (a) the average results obtained from using CNSN+USTA data are shown with black squares and using only the CNSN data are shown with blue oblique crosses; (b) comparison to get a general average difference in both cases. Uncertainties are obtained from the output files of the hypoDD program and shown by vertical lines; and of them are too small to be visible.

Supporting the assumption that the DD algorithm is sensitive to the seismic network coverage, when both CNSN and USTA data were used, the number of events in each cluster increased (Figure 4.9). The obtained results showed the distribution of relocated epicentres using both CNSN and USTA data had slightly changed as follows:

- The use of V1 and V2 showed the majority of events had slightly relocated toward the west. The average movement was less than 0.85 km for large events and about 2.56 km for small events along the longitude. Minor movements were observed along the latitude (Figures 4.9(a) and 4.9(b)).
- With V3, the average movement was about 2.56 km westward along the longitude and about 2.22 km toward the south along the latitude (Figure 4.9(c)).
- With V4, the majority of events showed relocation toward the west of about 1.71 km along the longitude and about 1.11 km toward the south along the latitude (Figure 4.9(d)).
- V5 exhibited no ordered relocation, with an average movement of 1.71 km along the longitude and 1.11 km along the latitude (Figure 4.9(e)).

In general, the relocated epicentres using V1, V2 and V5 were more tightly clustered, suggesting that these models may be the more accurate velocity models in estimation of earthquake location by the DD technique in the region. The overall pattern of seismicity was more focussed when both CNSN and USTA data sets were used and V1, V2 and V5 were applied. This pattern can be defined as a linear feature that may be a fault with a northwest-southeast striking plane, similar to the regional pattern of seismicity.

Figure 4.9: Epicentral distributions of the Val-des-Bois earthquake aftershocks using the velocity model (a) V1, (b) V2, (c) V3, (d) V4 and (e) V5. The blue circles show hypocentres obtained by using only the CNSN data, and the green stars, yellow-green diamonds, brown plus, pink triangles and violet stars show the relocated hypocentres obtained by using both CNSN and USTA data for V1, V2, V3, V4 and V5, respectively. The sizes of the symbols are proportional to the magnitude. The directions of hypocentre movements are shown by arrows.

Figure 4.10 presents the hypocentral projections of the relocated events of Set #1 in two cases: (a) when both CNSN and USTA data were used and (b) when only the CNSN data were utilized. It seems that by taking advantage of USTA data, the number of events involved in clusters increased and errors decreased. Although both of these projections

suggest a fault plane striking northwest-southeast, it can be interpreted that the apparent trend of seismicity changed slightly when only CNSN data were used.

Figure 4.10: Comparison between the hypocentral projections of the Val-des-Bois earthquake aftershocks obtained with velocity model V1 and MAXSEP = 5 km using (a) both CNSN + USTA data and (b) only the CNSN data. In each figure, the upper-left panel shows the distribution of stations that were used in the hypocentral determination; the upper-right panel shows the distribution of epicentres with error bars. There are two cross sections shown as A-A' and B-B' in the upper-right panels: the orientations of these cross-sections were chosen along and across the seismicity trend. The hypocentral projection on cross-section A-A' is illustrated in the bottom-left panel, and the projection on cross-section B-B' is displayed in the bottom-right panel.

The average epicentral distribution of the Val-des-Bois earthquake aftershocks obtained by using only the CNSN data and both CNSN+USTA data using V1 are shown in Figure 4.11. The standard deviation indicators are also displayed in this figure. The values of the epicentral location uncertainty measurement indicate the relatively higher uncertainty when only the CNSN data were used compared to using both CNSN and USTA data.

Overall, distributions of the relocated epicentres using both CNSN and USTA data demonstrated slight movement toward the southwest. These movements were more considerable in small events.

Figure 4.11: Average epicentral distributions of the Val-des-Bois earthquake aftershocks obtained by using only the CNSN data and both CNSN+USTA data, which are shown by orange diamonds and blue squares, respectively. Uncertainties come from the output file of program and are shown by the vertical and horizontal black lines.

4.2.1 Comparison of the Relocated Epicentres of the Val-des-Bois Aftershocks through the VELEST and hypoDD Programs using CNSN+UATA Data

In the next step, the events in Set #1 were relocated through the JHD method using both the CNSN and USTA data. The resulting relocated epicentres were compared with the results obtained by the DD method using V5 and those of the GSC catalog and are presented in Figure 4.12. The comparison of the results using the same velocity model but various methods shows almost the same pattern for the seismicity trend. The number of relocated events were decreased in the DD method, because some events lost their linkage during relocation. The relocated epicentres were more tightly clustered when hypoDD was applied. However, the values of the uncertainties relatively decreased when the JHD method was used.

The distribution of the relocated epicentres when using the JHD method (compared to the DD method) and both CNSN and USTA data demonstrate slight movement toward the southwest.

Figure 4.12: Comparison of the relocated epicentres of the Val-des-Bois aftershocks obtained by different methods, but with the same models using both CNSN+USTA data. The results obtained by hypoDD using V5 are presented by the dark triangles; the results obtained by the VELEST are presented by the red crosses; and the epicentres in the GSC catalog are presented by the blue circles. Uncertainties come from the output files of programs and are shown by the vertical and horizontal lines.

The locations of events using the JHD method exhibited slightly more similarity with those in the GSC catalog data set, in terms of maximum and minimum epicentral displacement when the USTA data were included. It may be due to the impact of more travel time data in the determination of the epicentres.

Figure 4.13 shows the distributions of the relocated epicentres using only the CNSN dataset and using both the CNSN and USTA data set. The uncertainties are also displayed in this figure. There were no remarkable changes in the values of the epicentral uncertainties measurement when only the CNSN data were used compared to using both CNSN and USTA data.

The overall pattern of seismicity was not considerably changed when both CNSN and USTA data sets were used. The majority of events were aligned in a northwest-southeast direction, which can be defined as a linear feature and may be a fault with a northwest-southeast striking plane similar to the regional seismicity pattern. The other remaining events show an almost north-south seismicity trend.

Figure 4.13: Epicentral distributions of the Val-des-Bois earthquake aftershocks obtained using only the CNSN data and both the CNSN+USTA data through the JHD method are represented by the blue squares and green stars, respectively. Uncertainties come from the output file of program and are shown by the vertical and horizontal lines.

4.3 DOUBLE-DIFFERENCE ANALYSIS OF THE LADYSMITH AFTERSHOCKS USING ONLY THE CNSN DATA

The Ladysmith earthquake with a magnitude (M_W) of 4.6 and a focal depth of about 12-14 km occurred on May 17, 2013. This event occurred on a northwest striking oblique thrust fault about 18 km northeast of Shawville in southwestern Quebec in the Western Quebec Seismic Zone (WQSZ) (Bent et al., 2015).

A total of 50 events with a magnitude (M_N) range of between 0.9 and 5.2 were recorded for the Ladysmith earthquake (Set #2), as outlined in Table 4.3. The distribution of these aftershocks is shown in Figure 4.14.

Table 4.3: Summary of the studied aftershock sequences of the Ladysmith earthquake occurring during 2013-2015. * and ** show focal depths have been calculated using RDPM and free depth, respectively. The “g” means the depth was fixed. (Canadian Seismic Activity-Provisional Summary-Observatory Crescent and Pacific Geoscience Centre, GSC, Canadian National Earthquakes Database (CNED)).

No.	Date	Time (UT)	Lat (°N)	Long (°W)	Depth (km)	Mag (M_N)	Region
1	2013/05/17	13:43:23	45.74	76.34	*13.5g, **13.57	5.2	18 km NE from Shawville, QC, Mainshock, Felt
2	2013/05/17	13:53:55	45.75	76.35	*14.0g, **14.02	4.1	20 km NE from Shawville, QC, aftershock. Felt
3	2013/05/17	14:16:18	45.75	76.37	12.0g	1.4	19 km NE from Shawville, QC, aftershock
4	2013/05/17	14:46:12	45.77	76.36	14.5	1.7	21 km NE from Shawville, QC, aftershock
5	2013/05/17	16:22:02	45.73	76.33	12.0g	1.5	19 km NE from Shawville, QC, aftershock
6	2013/05/17	17:46:07	45.75	76.34	14.5	2.1	19 km NE from Shawville, QC, aftershock
7	2013/05/17	17:50:36	45.72	76.35	9.9	2.1	19 km NE from Shawville, QC, aftershock
8	2013/05/17	19:31:46	45.76	76.35	14.4	1.7	21 km NE from Shawville, QC, aftershock
9	2013/05/17	19:59:31	45.74	76.37	11.4	1.6	18 km NE from Shawville, QC, aftershock
10	2013/05/17	20:15:17	45.75	76.35	14.0	3.2	20 km NE from Shawville, QC, aftershock. Felt

11	2013/05/17	22:29:22	45.74	76.36	12.0g	1.5	18 km NE from Shawville, QC, aftershock
12	2013/05/18	02:46:44	45.75	76.34	12.0g	1.1	19 km NE from Shawville, QC, aftershock
13	2013/05/18	04:54:11	45.74	76.36	12.0g	1.0	18 km NE from Shawville, QC, aftershock
14	2013/05/19	09:46:40	45.75	76.34	12.0g	1.3	20 km NE from Shawville, QC, aftershock
15	2013/05/19	10:29:37	45.74	76.37	12.0g	1.0	18 km NE from Shawville, QC, aftershock
16	2013/05/19	15:59:01	45.75	76.35	12.0g	1.1	19 km NE from Shawville, QC, aftershock
17	2013/05/19	16:14:28	45.72	76.35	12.0g	1.2	17 km NE from Shawville, QC, aftershock
18	2013/05/19	20:54:40	45.74	76.36	12.0g	1.2	18 km NE from Shawville, QC, aftershock
19	2013/05/20	02:48:39	45.76	76.35	12.0g	1.3	20 km NE from Shawville, QC, aftershock
20	2013/05/20	14:21:59	45.76	76.35	12.g	1.7	21 km NE from Shawville, QC, aftershock
21	2013/05/20	23:16:05	45.75	76.33	12.0g	1.6	21 km NE from Shawville, QC, aftershock
22	2013/05/21	04:23:28	45.74	76.35	12.0g	1.1	19 km NE from Shawville, QC, aftershock
23	2013/05/21	15:38:18	45.75	76.36	12.0g	1.7	19 km NE from Shawville, QC, aftershock
24	2013/05/22	02:47:26	45.74	76.36	12.0g	1.0	18 km NE from Shawville, QC, aftershock
25	2013/05/23	13:49:49	45.75	76.37	12.g	1.7	19 km NE from Shawville, QC, aftershock
26	2013/05/24	13:16:59	45.75	76.36	12.0g	2.0	19 km NE from Shawville, QC, aftershock
27	2013/05/24	19:48:08	45.74	76.35	14.6	2.8	20 km NE from Shawville, QC, aftershock. Felt
28	2013/05/25	01:08:05	45.75	76.38	12.0g	1.4	18 km NE from Shawville, QC, aftershock
29	2013/05/25	01:10:06	45.75	76.35	12.0g	1.4	20 km NE from Shawville, QC, aftershock
30	2013/05/26	03:05:41	45.74	76.34	12.0g	1.4	19 km NE from Shawville, QC, aftershock
31	2013/05/27	07:09:48	45.75	76.38	12.0g	1.3	18 km NE from Shawville, QC, aftershock
32	2013/05/28	00:43:29	45.73	76.35	12.0g	1.6	18 km NE from Shawville, QC, aftershock
33	2013/05/30	05:34:58	45.75	76.35	*13.5g, **12.97	3.7	19 km NE from Shawville, QC, aftershock. Felt
34	2013/05/30	08:09:45	45.74	76.37	12.0g	0.9	18 km NE from Shawville, QC, aftershock
35	2013/06/08	07:04:47	45.75	76.34	13.0	1.9	20 km NE from Shawville, QC, aftershock
36	2013/06/09	06:07:38	45.75	76.36	12.0g	1.1	19 km NE from Shawville, QC, aftershock
37	2013/06/10	10:38:59	45.75	76.37	12.0g	1.5	19 km NE from Shawville, QC, aftershock

38	2013/06/15	15:58:31	45.74	76.35	13.3	2.5	19 km NE from Shawville, QC, aftershock
39	2013/06/22	04:25:57	45.74	76.35	13.2	1.4	19 km NE from Shawville, QC. aftershock
40	2013/06/30	08:40:46	45.75	76.35	14.0	3.1	19 km NE from Shawville, QC, aftershock. Felt
41	2013/06/30	08:49:08	45.75	76.37	12.0g	1.0	19 km NE from Shawville, QC, aftershock
42	2013/07/21	08:13:28	45.74	76.35	13.5	1.9	19 km NE from Shawville, QC, aftershock
43	2013/08/20	11:00:22	45.73	76.36	12.0g	1.9	17 km NE from Shawville, QC, aftershock
44	2013/10/12	04:04:08	45.77	76.34	18.0g	1.5	22 km NE from Shawville, QC
45	2013/11/16	12:50:39	45.75	76.34	18.0g	2.9	20 km NE from Shawville, QC. Felt
46	2013/11/18	13:37:22	45.75	76.35	18.0g	2.1	20 km NE from Shawville, QC, aftershock. Felt
47	2014/02/13	04:04:56	45.73	76.34	18.0g	1.9	18 km NE from Shawville, QC
48	2014/03/16	16:17:42	45.73	76.21	18.0g	1.4	24 km NW from Wakefield, QC
49	2015/02/25	05:54:27	45.69	76.16	18.0g	1.4	19 km W from Wakefield, QC
50	2015/09/09	19:17:50	45.76	76.34	*14.5	3.7	21 km NE of Shawville, QC

Figure 4.14: Distribution of the 50 aftershock sequences of the 2013 Ladysmith earthquake shown by empty circles. The size of the circles is proportional to the magnitude.

In this study, 50 aftershocks of the Ladysmith earthquake were relocated using the hypoDD program and five velocity models. The hypoDD program was run using only the CNSN data (without using the USTA data set). The resulting relocated hypocentres using V1 are

presented in Table 4.4. The clustered distributions of the relocated epicentres, using all five different velocity models, and those of the GSC catalog are presented in Figure 4.15.

Table 4.4: Relocated hypocentres of the Ladysmith earthquake aftershocks using only the CNSN data, calculated from the hypoDD program using MAXSEP = 5, NITER = 2 & V1. The negative longitude values indicate degrees west.

ID	Lat	Long	Yr	Mo	Dy	Hr	Min	Sec	Mag	Depth	
										Catalog	hypoDD
1	45.737577	-76.340047	2013	5	17	13	43	23.930	5.2	13.50	13.91
2	45.744722	-76.344263	2013	5	17	13	53	55.100	4.1	14.00	13.68
4	45.772205	-76.358187	2013	5	17	14	46	12.400	1.7	14.48	14.83
5	45.732703	-76.337541	2013	5	17	16	22	2.690	1.5	12.00	12.68
6	45.745630	-76.340454	2013	5	17	17	46	7.200	2.1	14.48	13.18
7	45.732874	-76.354313	2013	5	17	17	50	36.560	2.1	9.91	11.18
8	45.759273	-76.356844	2013	5	17	19	31	46.920	1.7	14.43	14.57
9	45.739624	-76.365796	2013	5	17	19	59	31.920	1.6	11.45	12.58
10	45.745504	-76.347388	2013	5	17	20	15	17.920	3.2	13.96	13.81
11	45.736381	-76.347412	2013	5	17	22	29	22.180	1.5	12.00	12.45
19	45.758582	-76.360197	2013	5	20	2	48	39.570	1.3	12.00	13.12
21	45.755131	-76.329964	2013	5	20	23	16	5.520	1.6	12.00	12.74
26	45.739075	-76.357267	2013	5	24	13	16	59.420	2.0	12.00	11.21
27	45.742065	-76.342090	2013	5	24	19	48	8.640	2.8	14.56	13.80
32	45.735571	-76.349715	2013	5	28	0	43	29.810	1.6	12.00	12.74
33	45.743840	-76.351139	2013	5	30	5	34	58.690	3.7	13.50	13.59
35	45.745695	-76.344743	2013	6	8	7	4	47.570	1.9	12.98	13.54
38	45.743982	-76.351001	2013	6	15	15	58	31.680	2.5	13.33	13.50
39	45.741443	-76.352238	2013	6	22	4	25	57.600	1.4	13.19	13.22
40	45.748348	-76.356795	2013	6	30	8	40	47.140	3.1	13.97	12.32
42	45.744576	-76.347030	2013	7	21	8	13	28.270	1.9	13.46	13.64
43	45.734851	-76.358488	2013	8	20	11	0	22.540	1.9	12.00	12.06
44	45.758069	-76.338273	2013	10	12	4	4	8.710	1.5	18.00	16.85
45	45.746411	-76.343270	2013	11	16	12	50	39.710	2.9	18.00	17.62
46	45.760181	-76.353434	2013	11	18	13	37	22.410	2.1	18.00	16.76
47	45.734285	-76.342904	2014	2	13	4	4	56.010	1.9	18.00	18.16
50	45.760579	-76.339950	2015	9	9	19	17	50.520	3.7	14.50	14.00

Figure 4.15: Clustered epicentral distributions of Ladysmith aftershocks using only the CNSN data. The blue circles show the GSC catalog epicentres. The white stars, green-yellow diamonds, black plus symbols, pink triangles, and light brown squares represent the relocated epicentres using velocity models V1, V2, V3, V4 and V5, respectively. The sizes of the symbols are proportional to the magnitude. The directions of epicentre movement of two events are shown by arrows.

The relocated epicentres of Set #2 obtained with all velocity models showed a northwest-southeast seismicity trend, compatible with the seismicity pattern in this region. However, locations using V1 and V5 exhibited the most similarity with those using the GSC catalog

data set, in terms of maximum and minimum epicentral displacement. The reason for this similarity is that V1 is usually used in the determination of the seismic parameters in the GSC catalog (as a standard model for this region). Also, V1 was selected as an initial model in the VELEST program, which provides V5.

V2 and V4 showed larger deviations, in terms of maximum and minimum epicentral displacement. It seems that the epicentres resulting from V2 and V4 were systematically shifted. The values of velocities V2 were related to the north side of Ottawa-Bonnechere graben and were obtained using the Rayleigh-wave data around the epicentre of the Val-des-Bois earthquake and were relatively lower than those of the other models. The values of velocities V4 were related to the southeast Ontario and were relatively higher than those of the other models. This reason may be a possible explanation for those shifts.

Figure 4.16 shows the distance, regardless of direction, between the relocated epicentres for the Ladysmith aftershocks using all five velocity models and those of the GSC catalog. Event 44 in V4 had large differences between the relocated and original epicentres in the catalog about 30 km. These large differences may have been related to inaccuracy in reading arrival times, the number of available phases or the applied velocity models, which are some factors that control the accuracy of hypocentral locations. Since all factors were kept the same in all trials, it seems that this large difference was a result of the used velocity model. Event 8 showed a small difference between the relocated epicentres and the original epicentres in the catalog about 0.2 km.

Figure 4.16: Epicentral distances between catalog and relocated Ladysmith aftershocks using only the CNSN data and five different velocity models. The distances between relocated epicentres obtained from V1, V2, V3, V4 and V5 and epicentres in the GSC catalog are represented by squares, diamonds, upward triangles, downward triangles and oblique crosses, respectively. Standard deviations of the average distances are shown by vertical black lines.

4.3.1 Comparison of the Relocated Epicentres of the Ladysmith Aftershocks using the VELEST and hypoDD Programs using only CNSN Data

The events in Set #2 were relocated using the JHD method through the VELEST program using only the CNSN data. The resulting relocated epicentres were compared with the results obtained by the DD method through hypoDD program using V5, presented in Figure 4.17. It should be noted that V5 was obtained from the VELEST program. The comparison of the results using the same velocity model but various methods showed almost the same pattern of seismicity trends. However, the value of uncertainties decreased when the JHD method was applied.

Figure 4.17: Comparison of the relocated epicentres of the Ladysmith aftershocks obtained by different methods, but with the same models, using only CNSN data. The results obtained by the hypoDD using V5 are represented by the dark triangles, the results obtained by the VELEST are represented by red crosses, and the epicentres in the GSC catalog are represented by blue circles. Uncertainties come from the output files of programs and are shown by the vertical and horizontal lines.

4.4 DOUBLE DIFFERENCE ANALYSIS OF THE LADYSMITH AFTERSHOCKS USING CNSN AND USTA DATA

In the next step, the aftershock sequence of the Ladysmith earthquake was relocated using both CNSN and USTA data sets in the hypoDD program and five velocity models. Figures A.19 – A.36 and Tables A.18 – A.29 in Appendix A display the relocated hypocentres for Ladysmith aftershocks. The following presented results were obtained using five km for MAXSEP.

Figure 4.18: Clustered epicentral distributions of Ladysmith aftershocks using both CNSN+USTA data. The blue circles show the GSC catalog epicentres. The white stars, green-yellow diamonds, black plus symbols, pink triangles, and light brown squares represent the relocated epicentres using velocity models V1, V2, V3, V4 and V5, respectively. The sizes of the symbols are proportional to the magnitude. The directions of epicentre movement of nine events are shown by arrows.

The clustered distributions of the relocated epicentres of Set #2 obtained from hypoDD using all five velocity models and those of the GSC catalog are presented in Figure 4.18.

The relocated epicentres obtained from different provided velocity models showed the same seismicity trend along the northwest-southeast direction, which is compatible with the seismicity pattern in this region. However, the relocated epicentres obtained from V1 and V2 and V3 had the most similarity to the GSC catalog data set, in terms of maximum and minimum epicentral displacement. To have a better visual than the clustered Figure 4.18, the epicentral distribution of some of the biggest aftershocks of the Ladysmith event is presented in Figure 4.19.

Figure 4.19: Epicentral distributions of some of the biggest Ladysmith event aftershocks. The blue circles show the GSC catalog epicentres, and the relocated epicentres using V1, V2, V3, V4 and V5 are represented by white stars, green-yellow diamonds, black plus symbols, pink triangles and light brown squares, respectively. The sizes of the symbols are proportional to the magnitude. The directions of epicentre movement of four events are shown by arrows.

Figure 4.20 shows the distance, regardless of direction, between the relocated epicentres of Set #2 using all five velocity models and those of the GSC catalog. Events 21 and 47 in V4 exhibited large differences between the relocated epicentres and the original epicentres in the catalog about 7.1 and 5.0 km, respectively. Events 2 and 45 showed small differences

between the relocated epicentres and the original epicentres in the catalog about 0.3 and 1.0 km, respectively. The relocated epicentres resulting from the V1, V2, V3 and V5 displayed less displacement from the catalog epicentres than those obtained with V4. The relocated epicentres obtained from V4 showed the highest distances. One possible explanation for these differences may be due to the higher values of the velocities of the crustal depths in V4 than those of the other models.

Figure 4.20: Epicentral distances between catalog and relocated Ladysmith aftershocks using five different velocity models. The distances between relocated epicentres obtained from V1, V2, V3, V4 and V5 and epicentres in GSC catalog are represented by squares, diamonds, upward triangles, downward triangles and oblique crosses, respectively. Standard deviations of the average distances are shown by vertical black lines.

The average uncertainties in epicentral differences between the relocated epicentres of Set #2 and those in the GSC catalog for each velocity model are shown in Figure 4.21(a). It

seems that event 26 presented the most uncertainties. Regardless of this event, all velocity models, except V3, had relatively low uncertainties. The average differences between the relocated epicentres and the ones in the GSC catalog when using only the CNSN data and both CNSN and USTA data are presented in Figure 4.21(b). The difference was larger when only the CNSN data were used. This may be due to the reading of more arrival times when combined data set was used, which resulted in greater accuracy in relocation estimations. It should be mentioned that the original locations in the GSC catalog included some of the USTA data, which were routinely used for location determinations after the Ladysmith earthquake.

The uncertainties are also displayed in Figure 4.21. The values of the epicentral distance uncertainties measurement indicated the relatively higher uncertainties in locations of events when only the CNSN data were used compared to using both CNSN and USTA data.

Figure 4.21: Epicentral distances between catalog data and relocated Ladysmith aftershocks using five velocity models: (a) the average results obtained using CNSN+USTA data are represented by black squares, and only the CNSN data are represented by blue oblique crosses, and (b) comparison to get a general average difference in both cases. Uncertainties are obtained from the output files of the hypoDD program and shown by the vertical lines; Some of them are too small to be visible.

The results of epicentral relocations showed that clusters contained higher numbers of the relocated events (Figure 4.22); and, compared to the previous results (using only the CNSN data), there were almost high differences between the hypocentral locations. Distributions of the relocated epicentres using both CNSN and USTA data slightly changed as follows:

- Using V1 showed trivial relocation in large events and more notable movement in small events. The average movement was about 1.11 km toward the south along the latitude. No remarkable changes were observed along the longitude (Figure 4.22(a)).
- With V2, the trend of epicentral distribution totally moved toward the southeast, about 3.42 km toward the east along the longitude and about 2.78 km toward the south along the latitude (Figure 4.22(b)). The epicentres using only the CNSN data in this model were different from most other models, while when using both data sets, they are more similar. One possible explanation for this variation, may have been the different study area for which V2 was defined. However, uncertainties in locations with this model were comparable to those from other models.
- With V3, the relocation was about 1.71 km toward the east along the longitude, and there was no remarkable movement along the latitude (Figure 4.22(c)).
- Considerable epicentral changes were observed with the use of V4 about 5.98 km toward the east along the longitude and about 5.55 km toward the south along the latitude (Figure 4.22(d)). Also, the epicentres resulting from V4 were very different for both data sets, due to the higher values of the velocities of the crustal depths in this model compared to those of the other models. The locations shifted to the west

when using only the CNSN data and moved to the east when both CNSN and USTA data were used.

- With V5, the average relocation was about 1.71 km toward the east along the longitude and 1.11 km toward the south along the latitude (Figure 4.22e)).

In general, the relocated epicentres using V1 and V5 were more tightly clustered, suggesting that these models may have been the more accurate velocity models in the estimation of earthquake location by the DD technique in the region. The overall pattern of seismicity was more focused when both CNSN and USTA data sets were used and V1 and V5 were applied. This pattern can be defined as a linear feature that may be a fault with a northwest-southeast striking plane similar to the regional seismicity pattern. If it compares to the focal mechanism (see Section 6.1), the probable fault plane would be a 130° striking plane and 54° dip angle (similar to the focal mechanism solution).

Figure 4.22: Epicentral distributions of the Ladysmith earthquake aftershocks using: (a) V1, (b) V2, (c) V3, (d) V4 and (e) V5. The blue circles represent hypocentres obtained by using only the CNSN data; and, the green stars, yellow-green diamonds, brown plus, pink triangles and violet stars represent the relocated hypocentres obtained by using both CNSN and USTA data for V1, V2, V3, V4 and V5, respectively. The sizes of the symbols are proportional to the magnitude. The directions of hypocentre movement are shown by arrows.

Figure 4.23 presents the hypocentral projections of the relocated events of Set #2 when both CNSN and USTA data were used and when only the CNSN data were. It seems that by taking advantage of the USTA data, the number of events which are participated in clusters increased and errors decreased. Although both of these projections suggest a fault

plane striking northwest-southeast, it can be interpreted that the apparent trend of seismicity slightly changed when only the CNSN data were used.

Figure 4.23: Comparisons between the hypocentral projections of the Ladysmith earthquake aftershocks obtained by using (a) both CNSN + USTA data and (b) only the CNSN data. V1 and MAXSEP=5 km were used. In each figure, the upper-left panel shows the distribution of stations that were used in hypocentral determination; and, the upper-right panel shows the distribution of epicentres with error bars. There are two cross sections, shown as A-A' and B-B' in upper-right panel. The orientations of these cross sections were chosen along and across the seismicity trend. The hypocentral projection on cross section A-A' is illustrated in the bottom-left panel; and, the projection on cross section B-B' is displayed in the bottom-right panel.

The average epicentral distribution of the Ladysmith earthquake aftershocks obtained by using only the CNSN data and both CNSN and USTA data are shown in Figure 4.24. The standard deviation indicators are also displayed in this figure. The values of the epicentral location uncertainty measurement indicate relatively higher uncertainty when only CNSN data were used compared to the use of both CNSN and USTA data sets.

Overall, the distribution of the relocated epicentres using both CNSN and USTA data, which was less scattered, demonstrated slight movement toward the southeast. These movements were more considerable in small events, because they are not well recorded by stations and their locations cannot be reliably determined due to insufficient station coverage. The locations of these events can be well determined if there is a sufficient coverage in the number and distribution of stations. Therefore, when the combined data set was used, those small events showed remarkable shifts in their locations.

Figure 4.24: Average epicentral distributions of the Ladysmith earthquake aftershocks obtained using only the CNSN data and both CNSN+USTA data are represented by orange diamonds and blue squares, respectively. Standard deviations are shown by vertical and horizontal black lines.

4.4.1 Comparison of the Relocated Epicentres of the Ladysmith Aftershocks through the VELEST and hypoDD Programs using CNSN+UATA Data

In the next step, the events in Set #2 were relocated through the JHD method using both the CNSN and USTA data sets. The resulting relocated epicentres were compared with the results obtained by the DD method using V5 and those of the GSC catalog and presented in Figure 4.25. The comparison of the results using the same velocity model but various methods shows almost the same pattern of seismicity trends. The number of relocated events decreased in DD method, because some events lost their linkage during relocation. The relocated epicentres were more tightly clustered when the hypoDD was applied. However, the value of uncertainties changed slightly when the JHD method was used.

The distribution of the relocated epicentres with the use of the JHD method (compared to the DD method) and both CNSN and USTA data sets demonstrated slight movement toward the southwest.

Figure 4.25: Comparison of the relocated epicentres of the Ladysmith aftershocks obtained by different methods, but with the same models, using both CNSN+USTA data. The results obtained with hypoDD using the V5 are represented by dark triangles, the results obtained by VELEST are represented by red crosses, and the epicentres in the GSC catalog are represented by blue circles. Uncertainties come from the output files of programs and are shown by the vertical and horizontal lines.

The locations of events using the JHD method showed more similarity with those in the GSC catalog dataset, in terms of maximum and minimum epicentral displacement, when the USTA data were included. This may be due to the impact of more travel time data in the determination of the epicentres.

Figure 4.26 shows distributions of the relocated epicentres using only the CNSN data set and using both the CNSN and USTA data sets. The uncertainties are also displayed in this figure. There were no remarkable changes in the values of the epicentral uncertainty measurements between the use of only the CNSN data and both CNSN and USTA data sets.

The overall pattern of seismicity was not considerably changed when both the CNSN and USTA data sets were used. The relocated events were aligned in a northwest-southeast direction, which can be defined as a linear feature and may be a fault with a northwest-southeast striking plane similar to the regional seismicity pattern.

Figure 4.26: Epicentral distributions of the Ladysmith earthquake aftershocks obtained using only the CNSN data and both CNSN+USTA data through the JHD method are represented by blue squares and green stars, respectively. Uncertainties come from the output file of program and are shown by the vertical and horizontal lines.

4.5 EIGHTEEN EVENTS USING ONLY THE CNSN DATA

In this part, 18 earthquakes with magnitudes of 3.0 or greater ($M_N \geq 3.0$) that occurred from January 2013 through July 2015 in the WQSZ (Set #3) were studied using the travel times of the primary (P) and secondary (S) waves. The geographical distribution of the studied earthquakes is shown in Figure 4.27. Based on this figure, the epicentral distribution of the

most events in Set #3 exhibited a northwest trend, which is in agreement with the trend of historical seismic activity in the WQSZ. The other events revealed a northeast trend. A summary of the defining parameters of each event including magnitude and hypocentral location is given in Table 4.5.

Figure 4.27: Distribution of the studied earthquakes epicentres in the WQSZ from January 2013 through July 2015.

Table 4.5: Summary of the studied earthquakes in the WQSZ that occurred from January 2013 to July 2015. *Focal depths have been calculated using RDPM, **Free depth and good azimuthal distribution, ***Default free depth because of poorly azimuthal coverage. (Canadian Seismic Activity - Provisional Summary - Observatory Crescent and Pacific Geoscience Centre, GSC, Canadian National Earthquakes Database (CNED)).

No.	Date	Time (UT)	Lat (°N)	Long (°W)	Depth (km)	Mag (M _N)	Region	Name (in this study)
1	20130116	00:53:05	46.04	75.45	21.00*	3.5	18 km NE from Val-des-Bois, QC	20130116-A
2	20130116	01:01:49	46.05	75.43	18.00***	3.0	21 km NE from Val-des-Bois, QC	20130116-B
3	20130415	13:32:25	45.78	74.44	12.80**	3.1	11 km N from Brownsburg-Chatham, QC	20130415
4	20130517	13:43:23	45.74	76.34	13.50* /13.57**	5.2	18 km NE from Shawville, QC	20130517-A
5	20130517	13:53:55	45.75	76.35	14.00* /14.02**	4.1	20 km NE from Shawville, QC. Aftershock	20130517-B
6	20130517	20:15:17	45.75	76.35	14.00	3.2	20 km NE from Shawville, QC. Aftershock	20130517-C
7	20130521	20:43:01	45.44	74.20	18.00	3.4	9 km W from Oka-Kanesatake, QC	20130521
8	20130524	07:08:31	47.12	76.78	18.00	3.6	103 km NW from Maniwaki, QC	20130524
9	20130530	05:35:00	45.75	76.42	13.00	3.7	19 km NE from Shawville, QC. Aftershock	20130530
10	20130630	08:40:46	45.75	76.35	14.00	3.1	9 km NE from Shawville, QC, aftershock	20130630
11	20130904	01:52:12	46.65	75.57	18.00	3.1	10 km SW from Ferme-Neuve, QC	20130904
12	20131020	10:40:33	45.61	77.45	18.00	3.6	23 km NE from Barry's Bay, ON	20131020
13	20140207	15:45:05	45.09	73.65	12.50	3.1	21 km S from Saint-Remi, QC	20140207
14	20140330	03:47:15	46.95	76.46	18.00	3.0	73 km NW from Maniwaki, QC	20140330
15	20140704	22:55:57	45.92	74.86	18.00	3.0	8 km NE from Saint-Andre-Avellin, QC	20140704
16	20150404	17:23:00	46.76	75.80	18.00	3.0	27 km W from Ferme-Neuve, QC	20150404
17	20150420	10:13:43	46.77	73.29	14.50*	3.8	48 km NW from Shawinigan, QC	20150420
18	20150715	22:00:18	45.49	74.55	18.00	3.9	9 km SE from Vankleek Hill, ON	20150715

The distribution of the events' magnitudes is presented in Figure 4.28. Among the 18 studied events, 6 events were recorded with magnitudes between 3.5 and 4, and 10 events

had magnitudes of less than 3.5 (M_N). The strongest recorded events were 5.2 M_N of the May 17, 2013 Ladysmith earthquake and its aftershock with 4.1 magnitude.

Figure 4.28: Distribution of the magnitudes (M_N) of the studied events in Set #3

4.6 EIGHTEEN EVENTS USING CNSN AND USTA DATA

All events in Set #3 were analyzed using the travel times of the P- and S-waves using travel time through the Brune and Dorman velocity model (1963) and a combination of two sets of the CNSN and USTA waveforms (Section 3.4). Two series of runs were done. One series had a fixed depth at 18 km, and the other allowed the program to calculate the depth (free depth). A summary of the data parameters (root mean square, RMS, and maximum gap of azimuth) and hypocentres obtained from this method in both cases are presented in Table 4.6. The value of azimuthal gap can be useful in determination the reliability of the estimated hypocentre. A more reliable epicentre can be obtained with a smaller azimuthal

gap. In Figure 4.29, the resulting epicentres in case of the fixed depth and free depth are shown by green and yellow circles, respectively. The epicentral location of event 20130524 showed notable differences in two cases, which may have been due to the deficiency of seismic stations around it.

Table 4.6: Summary of the earthquake parameters of 18 events (Set #3) obtained for free and fixed depths using both CNSN+CNSN data.

Name	# Station	Az gap	Free depth			Fixed depth (18 km)		
			Lat (°N)	Long (°W)	RMS	Lat (°N)	Long (°W)	RMS
20130116-A	49	41	46.06	75.45	0.26	46.05	75.44	0.36
20130116-B	10	277	46.07	75.44	0.22	46.07	75.43	0.26
20130415	11	129	45.78	74.44	0.11	45.78	74.43	0.39
20130517-A	25	81	45.74	76.34	0.17	45.76	76.34	0.47
20130517-B	25	65	45.74	76.35	0.12	45.80	76.33	3.02
20130517-C	24	88	45.75	76.35	0.15	45.70	76.40	5.31
20130521	32	78	45.44	74.20	0.16	45.42	74.20	1.84
20130524	29	110	47.12	76.77	1.02	47.05	76.93	5.65
20130530	22	93	45.75	76.35	0.12	45.77	76.39	9.87
20130630	24	72	45.75	76.35	0.12	45.76	76.35	0.26
20130904	42	57	46.68	75.58	0.26	46.65	75.57	0.36
20131020	43	59	45.62	77.43	0.31	45.62	77.44	1.07
20140207	27	86	45.09	73.64	0.31	45.07	73.63	1.04
20140330	31	116	46.95	76.46	0.22	46.95	76.41	0.90
20140704	29	84	45.93	74.85	0.25	45.94	74.85	0.63
20150404	27	83	46.75	75.80	0.18	46.76	75.79	1.95
20150420	36	103	46.76	73.29	0.33	46.76	73.27	0.73
20150715	35	45	45.48	74.55	0.33	45.48	74.54	0.73

Figure 4.29: Distribution of the obtained earthquakes epicentres in the WQSZ from January 2013 through July 2015 (Set #3) using the travel time method and both CNSN+USTA data. Yellow circles represent epicentres in the free depth case and green circles represent epicentres in the fixed depth case. Some of the points plot on top of each other.

The azimuthal gap distribution of the events shows that more than 75% of events had azimuthal gaps of less than 100°; therefore, the calculated locations are relatively reliable.

The distributions of the relocated epicentres of Set #3 using both CNSN and USTA data sets and those of the GSC catalog (only the CNSN data) are presented in Figure 4.30. The GSC catalog epicentres are shown by the blue circles, and the relocated epicentres using both CNSN and USTA data set in case of free depths and fixed depths are shown by yellow and green circles, respectively. The epicentral location of event 20130524 shows a notable difference when the USTA data were included (D54A station), which may be due to compensation of the deficiency of seismic stations around it.

Figure 4.30: Distribution of the obtained earthquakes epicentres in the WQSZ from January 2013 through July 2015 (Set #3) using the DAN program. Yellow and green circles represent epicentres in the free and fixed depth cases (CNSN + USTA data), and blue circles represent epicentres in the GSC catalog (only the CNSN data). Some of the points plot on top of each other.

Distances between the original epicentres and the obtained epicentres with both free and fixed depths were calculated, and the results were compared and are shown in Figure 4.31. The maximum distance was in event 20130524 with a fixed depth, due to the insufficient density of stations until the USTA data were added. The relocated epicentres showed average distances from the original epicentres of 1.6 km distance using free depth and 3.2 km with using fixed depth.

Figure 4.31: Distances between the epicentres obtained by the DAN program using both free and fixed depths and the original epicentres. The epicentre location of events had an average distance of 1.6 km from the original epicentres using free depth and 2.5 km for using fixed depth.

The average epicentral distribution of the earthquakes in Set #3 obtained using only the CNSN data and both CNSN and USTA data sets are shown in Figure 4.32. The standard deviation indicators are also displayed in this figure. The values of the epicentral location uncertainty measurements indicated a relatively higher uncertainty when only the CNSN data were used.

Overall, the comparison between these results did not show any remarkable differences in epicentres with the addition the USTA data to the CNSN data. However, differences in the uncertainties of epicentres were seen in some events. In general, the inclusion of more data reduced the uncertainties of locations, although the uncertainties did not change in events 20130517-C and 20130509 where the additional USTA stations were close to the epicentres.

Figure 4.32: Average epicentral distributions of 18 events (Set #3). Epicentres resulting from only the CNSN data are represented by red squares and from both CNSN + USTA data are represented by blue squares. Uncertainties are obtained from program output and shown by the vertical and horizontal lines.

5. FOCAL DEPTH RELOCATION

Generally, the lack of a dense seismic network makes it challenging to figure out accurate earthquake depths for small earthquakes. Well-constrained epicentres for the earthquakes in the Western Quebec Seismic Zone (WQSZ) can be determined due to the sufficient density of the Canadian National Seismic Network (CNSN) coverage; however, obtaining reliable depths is difficult, since this requires one or more seismograph stations within a distance similar to the earthquake's depth. Therefore, a combination of the CNSN and US Transportable Array (USTA) data sets may be useful in the estimation of focal depths.

This chapter, which divided into three parts, describes the applied procedures for estimation of earthquakes focal depths with the addition of the USTA data to the CNSN data set.

In the first and second parts, the focal depths of aftershock sequences of the 2010 Val-des-Bois earthquake (Set #1) and aftershock sequences of the 2013 Ladysmith earthquake (Set #2) were relocated using the double-difference (DD) algorithm through the hypoDD program and then compared with the results obtained by the joint hypocentre determination (JHD) method through the VELEST program.

In the third part of this chapter, the focal depths were obtained for 18 earthquakes (Set #3). In order to determine the hypocentres, the standard travel time inversion method was used. In each part, two data sets, one from the CNSN and the other from the USTA, were combined; and, the results were compared.

5.1 VAL-DES-BOIS AFTERSHOCKS USING ONLY THE CNSN DATA

The resulting focal depths using the all five velocity models (V1, V2, V3, V4 and V5, as mentioned in Chapter 3) and only the CNSN data in hypoDD for the late part of the aftershock sequence of the Val-des-Bois earthquake are presented in Table 5.1. The close stations' distances to this event were 10, 20 and 60 km (VABQ, GAC and F57A stations, respectively).

The differences between recalculated depths using the five velocity models and those in the GSC catalog are shown in Figure 5.1. It should be noted that most of the focal depths in the catalog are fixed depth, and only the depths of events 5 and 37 were calculated. It can be seen that the maximum and minimum differences between relocated depths and fixed depths were about 3.7 km in V3 (for event 8) and about 0.02 km in V1 (for events 1 and 13). The maximum differences between relocated and calculated depths of events 5 and 37 were about 1.9 and 3.1 km, respectively, with V4. Moreover, the use V1 shows the least difference.

The maximum and minimum average differences between recalculated depths of Set #1 using the five velocity models and those in the GSC catalog were about 2.2 km (event 38) and 0.25 km (event 16), respectively.

Figure 5.2 displays the projections of the relocated hypocentres on vertical profiles along the longitude and latitude directions using all velocity models and compares them with those of the GSC catalog. The results illustrate various changes in depths.

Table 5.1: Comparison between recalculated depths in hypoDD (MAXSEP = 5 km) using only the CNSN data for five velocity models and those of the GSC catalog for Val-des-Bois earthquake aftershocks. Cases with no obtained results are shown by “-”. *means focal depth was fixed.

Event #	Depth (km) in Catalog	Relocated depth (km) in hypoDD using only the CNSN data				
		V1	V2	V3	V4	V5
1	18.00*	18.02 ± 0.37	-	17.09 ± 0.41	-	17.56 ± 0.40
5	20.40	19.91 ± 0.57	19.67 ± 0.40	21.57 ± 0.68	18.52 ± 0.79	19.31 ± 1.34
8	18.00*	18.95 ± 0.44	18.75 ± 0.40	21.73 ± 0.43	18.33 ± 0.54	18.71 ± 0.74
9	18.00*	-	-	-	-	-
11	18.00*	18.59 ± 0.37	18.60 ± 0.35	21.51 ± 0.41	18.22 ± 0.51	18.60 ± 0.63
12	18.00*	17.64 ± 0.32	-	17.01 ± 0.36	17.20 ± 0.46	17.34 ± 0.62
13	18.00*	18.29 ± 0.39	18.98 ± 0.35	18.00 ± 0.39	18.60 ± 0.51	$18.29 \pm .32$
15	18.00*	-	-	-	-	-
16	18.00*	-	16.13 ± 1.32	19.39 ± 1.09	17.82 ± 1.46	17.67 ± 0.30
19	18.00*	-	-	-	-	-
20	18.00*	17.46 ± 0.76	-	18.04 ± 0.80	17.39 ± 0.79	17.35 ± 0.62
23	18.00*	-	-	-	-	16.63 ± 1.37
24	18.00*	17.73 ± 1.01	17.91 ± 0.96	15.54 ± 1.05	-	17.56 ± 0.41
25	18.00*	16.59 ± 0.83	-	-	16.03 ± 0.82	16.14 ± 1.83
28	18.00*	17.59 ± 0.45	17.60 ± 0.40	17.09 ± 0.46	17.27 ± 0.54	17.41 ± 0.56
30	18.00*	16.31 ± 0.59	-	15.34 ± 0.63	16.36 ± 0.68	16.17 ± 1.80
31	18.00*	18.92 ± 0.51	19.47 ± 0.50	20.25 ± 0.49	19.05 ± 0.56	18.83 ± 0.85
33	18.00*	18.92 ± 1.34	19.94 ± 1.33	18.63 ± 1.09	20.03 ± 1.62	19.35 ± 1.38
35	18.00*	-	-	-	-	19.40 ± 1.40
36	18.00*	-	-	19.18 ± 0.91	18.11 ± 1.25	17.91 ± 0.06
37	15.00	-	15.82 ± 1.69	-	18.15 ± 3.38	16.97 ± 1.00
38	18.00*	20.41 ± 1.52	-	21.32 ± 1.22	18.85 ± 1.43	-
39	18.00*	19.67 ± 1.23	-	21.19 ± 0.80	-	19.33 ± 1.36
40	18.00*	-	15.85 ± 1.33	-	18.24 ± 2.47	17.41 ± 0.56
41	18.00*	17.90 ± 0.65	17.25 ± 0.70	16.24 ± 0.72	-	-
45	18.00*	-	-	-	-	-

Figure 5.1: Depth differences between the GSC catalog and the relocated Val-des-Bois aftershocks using only the CNSN data for five different velocity models. The differences between recalculated depths obtained from velocity models V1, V2, V3, V4 and V5 and the catalog are represented by squares, diamonds, upward triangles, downward triangles and oblique crosses, respectively. Uncertainties for all points, obtained from the output files of the hypoDD program, are shown by vertical lines.

The average hypocentres of Set #1 obtained using only the CNSN data on vertical profiles along the longitude and latitude directions are presented in Figure 5.10.

(a)

(b)

Figure 5.2: Comparison between recalculated hypocentres projection of the Val-des-Bois aftershocks using only the CNSN data with those in the GSC catalog (many of the catalog depths are fixed), along the longitude (a) and latitude (b) direction using MAXSEP =5 km and all velocity models. The blue circles represent the GSC catalog hypocentres and, relocated hypocentres using V1, V2, V3, V4 and V5 are shown by grey stars, green diamonds, black plus symbols, pink triangles and brown stars, respectively. Standard deviations are shown by vertical black lines.

5.1.1 Comparison of the Relocated Focal Depths of the Val-des-Bois Aftershocks through the VELEST and hypoDD Programs using only the CNSN Data

The events in Set #1 were relocated using the JHD method through the VELEST program using only the CNSN data. The resulting relocated focal depths were compared with the results obtained with the DD method through hypoDD using V5 and are presented in Table 5.2.

Figure 5.3 displays the projections of the relocated hypocentres on vertical profiles along the longitude and latitude directions using the JHD method and compares them with results obtained by the DD method and those of the GSC catalog. The comparison of the results using the same velocity model but various methods illustrate various changes in depths. However, the value of uncertainties decreased when the JHD method was applied.

Table 5.2: Comparison between recalculated depths obtained by VELEST and hypoDD (V5) using only the CNSN data and those of the GSC catalog for the Val-des-Bois earthquake aftershocks. Cases with no obtained results are shown by “-”. *means focal depth was fixed.

Event #	Depth (km) in Catalog	Relocated depth (km)	
		VELEST	hypoDD (V5)
1	18.00*	18.73 ± 0.59	17.56 ± 0.40
2	18.00*	18.54 ± 0.03	-
3	18.00*	16.76 ± 0.09	-
4	18.00*	19.18 ± 0.14	-
5	20.40	8.32 ± 0.12	19.31 ± 1.34
6	18.00*	21.08 ± 0.02	-
7	18.00*	18.25 ± 0.05	-
8	18.00*	18.12 ± 0.02	18.71 ± 0.74
9	18.00*	19.49 ± 0.46	-
10	18.00*	18.14 ± 0.02	-
11	18.00*	19.66 ± 0.13	18.60 ± 0.63
12	18.00*	18.55 ± 0.07	17.34 ± 0.62
13	18.00*	19.20 ± 0.10	$18.29 \pm .32$

14	18.00*	21.21 ± 0.14	-
15	18.00*	19.59 ± 0.08	-
16	18.00*	17.28 ± 0.14	17.67 ± 0.30
17	18.00*	16.69 ± 0.25	-
18	18.00*	14.74 ± 0.16	-
19	18.00*	17.90 ± 0.01	-
20	18.00*	21.23 ± 0.39	17.35 ± 0.62
21	18.00*	16.46 ± 0.19	-
22	18.00*	17.96 ± 0.05	-
23	18.00*	17.65 ± 0.05	16.63 ± 1.37
24	18.00*	17.95 ± 0.01	17.56 ± 0.41
25	18.00*	17.69 ± 0.31	16.14 ± 1.83
26	18.00*	14.01 ± 0.67	-
27	18.00*	17.20 ± 0.06	-
28	18.00*	16.73 ± 0.08	17.41 ± 0.56
29	18.00*	20.41 ± 0.06	-
30	18.00*	19.91 ± 0.30	16.17 ± 1.80
31	18.00*	18.11 ± 0.19	18.83 ± 0.85
32	18.00*	14.54 ± 0.21	-
33	18.00*	18.02 ± 0.01	19.35 ± 1.38
34	18.00*	18.17 ± 0.07	-
35	18.00*	15.24 ± 0.12	19.40 ± 1.40
36	18.00*	17.90 ± 0.05	17.91 ± 0.06
37	15.00	18.77 ± 0.23	16.97 ± 1.00
38	18.00*	15.43 ± 0.26	-
39	18.00*	15.90 ± 0.10	19.33 ± 1.36
40	18.00*	21.36 ± 0.16	17.41 ± 0.56
41	18.00*	15.95 ± 0.18	-
42	18.00*	21.71 ± 0.33	-
43	18.00*	18.89 ± 0.64	-
44	18.00*	14.38 ± 0.28	-
45	18.00*	19.50 ± 0.42	-

(a)

(b)

Figure 5.3: Comparison between recalculated hypocentres projection of the Val-des-Bois aftershocks obtained by the VELEST and hypoDD programs using only the CNSN data and those in the GSC catalog (many of the catalog depths are fixed), along the longitude (a) and latitude (b) directions using MAXSEP = 5 km. The blue circles represent the GSC catalog hypocentres and relocated hypocentres using the JHD and DD methods are represented by the red pluses and dark triangles, respectively. Uncertainties obtained from output files are shown by vertical lines.

5.2 VAL-DES-BOIS AFTERSHOCKS USING CNSN AND USTA DATA

In the next step, focal depths for Set #1 using all velocity models and both CNSN and USTA data sets in the hypoDD program were calculated and are presented in Table 5.3. The differences between recalculated depths using the five velocity models and those in the GSC catalog are shown in Figure 5.4. It can be seen that the maximum and minimum differences between the relocated depths and the fixed depths were about 2.6 km with V2 (event 38) and about 0.1 km with V1, V2 and V3 (event 1), respectively.

The maximum differences between the relocated and calculated depths of events 5 and 37 were about 1.4 and 2.5 km with V4 and V1, respectively. Moreover, the use of V2 resulted in the least differences for both events. In overall, relocated depths for event 5, which had a calculated depth in the catalog, using all velocity models indicated a relatively lower depth than its calculated depth. The relocated depths for event 37 exhibited greater depth compared to its calculated depth in the catalog.

The average depth differences between the recalculated depths of Set #1 and those of the GSC catalog were relatively lower than those using only the CNSN data. These smaller differences were associated with lower uncertainties, due to taking advantage of the sufficient dense station coverage within close epicentral distances to the focal depth. The station network geometry, accuracy of phase arrival times and structure of the velocity model are possible reasons for the uncertainties. The maximum and minimum average differences were about 2.0 km (event 35) and 0.20 km (event 1), respectively. These results suggest that adequate station coverage can reduce the errors in the determination of seismic events depths and provide more realistic estimations of focal depths.

Figure 5.5 displays the projections of the relocated hypocentres on vertical profiles along the longitude and latitude directions.

Table 5.3: Comparison between recalculated depths in hypoDD (MAXSEP = 5 km) using both CNSN + USTA data for five velocity models and those of the GSC catalog for the Val-des-Bois earthquake. Cases with no obtained results are shown by “-”. *means focal depth was fixed.

Event #	Depth (km) in Catalog	Relocated depth (km) in hypoDD using CNSN + USTA data				
		V1	V2	V3	V4	V5
1	18.00*	17.81 ± 0.05	18.05 ± 0.08	17.94 ± 0.35	17.71 ± 0.43	17.89 ± 0.18
5	20.40	19.67 ± 0.08	19.72 ± 0.05	19.46 ± 0.56	19.09 ± 0.69	19.38 ± 1.40
8	18.00*	18.62 ± 0.09	18.70 ± 0.08	18.61 ± 0.36	18.93 ± 0.46	19.16 ± 1.19
9	18.00*	19.00 ± 0.81	19.82 ± 0.38	19.93 ± 0.93	19.88 ± 0.94	18.46 ± 0.49
11	18.00*	18.44 ± 0.11	18.37 ± 0.11	18.52 ± 0.35	18.57 ± 0.44	18.83 ± 0.86
12	18.00*	17.52 ± 0.10	17.39 ± 0.05	-	16.76 ± 0.38	16.73 ± 1.23
13	18.00*	18.57 ± 0.21	18.87 ± 0.15	19.11 ± 0.29	18.25 ± 0.44	18.38 ± 0.41
15	18.00*	-	16.19 ± 0.10	16.91 ± 0.62	-	17.28 ± 0.72
16	18.00*	15.97 ± 1.75	16.94 ± 0.22	-	16.40 ± 0.88	18.75 ± 0.77
19	18.00*	-	-	-	-	-
20	18.00*	17.09 ± 0.22	17.36 ± 0.23	16.89 ± 0.80	17.75 ± 0.76	17.79 ± 0.18
23	18.00*	-	17.54 ± 0.10	17.15 ± 0.05	-	16.83 ± 1.17
24	18.00*	17.26 ± 0.60	17.67 ± 0.30	16.49 ± 1.03	17.43 ± 1.00	16.79 ± 1.18
25	18.00*	18.34 ± 1.19	18.11 ± 1.57	17.11 ± 0.75	16.31 ± 0.76	-
28	18.00*	17.40 ± 0.09	17.78 ± 0.12	17.42 ± 0.35	17.58 ± 0.44	17.62 ± 0.35
30	18.00*	16.53 ± 0.28	16.99 ± 0.14	16.04 ± 0.59	17.24 ± 0.63	17.41 ± 0.56
31	18.00*	18.72 ± 0.26	18.44 ± 0.30	19.07 ± 0.42	19.33 ± 0.52	20.05 ± 2.08
33	18.00*	19.69 ± 1.92	16.03 ± 1.97	-	-	-
35	18.00*	-	-	-	-	19.89 ± 1.90
36	18.00*	17.82 ± 0.17	18.80 ± 1.38	18.45 ± 0.91	18.43 ± 1.25	17.78 ± 0.19
37	15.00	17.49 ± 1.17	15.07 ± 1.73	-	17.21 ± 2.96	-
38	18.00*	18.01 ± 0.83	20.58 ± 1.51	19.04 ± 1.19	-	18.18 ± 0.21
39	18.00*	19.36 ± 1.63	-	18.67 ± 0.80	19.07 ± 1.06	19.77 ± 1.79
40	18.00*	16.25 ± 1.16	15.71 ± 1.67	-	17.18 ± 1.91	-
41	18.00*	17.84 ± 0.43	16.57 ± 1.01	-	17.64 ± 0.83	-
45	18.00*	-	-	-	-	-

Figure 5.4: Depth differences between the GSC catalog and relocated Val-des-Bois aftershocks using both CNSN and USTA data for five different velocity models. The differences between recalculated depths obtained from velocity models V1, V2, V3, V4 and V5 and depths in the catalog are represented by squares, diamonds, upward triangles, downward triangles and oblique crosses, respectively. Uncertainties for all points obtained from the output files of the hypoDD program are shown by vertical lines.

The average relocated focal depths with both CNSN and USTA data sets were compared with results of using only the CNSN data and are shown in Figure 5.6. Based on these results, the focal depths of events in Set #1 using the combined data set were more focused at a depth of ~18 km, ranging between 16.5 and 19.5 km.

The average depth differences from the GSC catalog when using both CNSN and USTA data sets were compared with results when using only the CNSN data and are shown in Figure 5.7. The values of the depth difference uncertainty measurements indicate a relatively higher uncertainty when only the CNSN data were used compared to when using both CNSN and USTA data sets.

Figure 5.5: Comparisons between recalculated hypocentres projection of the Val-des-Bois aftershocks along the longitude (a) and latitude (b) directions using $\text{MAXSEP} = 5$ km and five velocity models. The blue circles represent the GSC catalog hypocentres, and the relocated hypocentres using V1, V2, V3, V4 and V5 are represented by grey stars, green-yellow diamonds, black plus symbols, pink triangles and brown stars, respectively. Standard deviations are shown by vertical black lines.

Figure 5.6: Average relocated focal depths of Set #1. The black squares represent the use of both CNSN+USTA data, and the blue diamonds represent the use of only the CNSN data. Standard deviations are shown by vertical lines.

Figure 5.7: Average depth differences of Set #1 from the GSC catalog. The black squares represent the use of both CNSN+USTA data, and the blue diamonds represent the use of only the CNSN data. Standard deviations are shown by vertical lines.

Figure 5.8 shows a three-dimensional (3D) plot of the average resulting relocated hypocentres using both CNSN and USTA data compared to the results obtained by using only the CNSN data. There were no obvious major trends revealed by the event relocations. However, changes in the hypocentre locations occurred.

It seems that events on the eastern side were relatively shallower than those on the western side, which can be interpreted as a plane with a west dipping direction. If it compares to the moment tensor solution obtained by Ma & Motazedian (2012) (see Appendix A), the probable fault plane would be a 330° striking plane with a dipping about 40° and a slip of about 92° .

The dominant seismogenic layer where this aftershock sequence occurred is located at a depth of about 16.5 to 19.5 km, which is compatible with most parts of the WQSZ; and, the thickness of this layer can be estimated at about 2.5 km.

Figure 5.8: Three-dimensional plot of the average relocated hypocentres of the Val-des-Bois aftershocks. The relocated hypocentres obtained using both CNSN+USTA data are represented by solid blue circles and only the CNSN data are represented by empty blue circles.

Figure 5.9 displays the projections of the relocated hypocentres on vertical profiles along the longitude and latitude directions using V1, V2, V3, V4 and V5. The figure presents the relocated depths when both the CNSN and USTA data sets were used and compares them with the recalculated depths when only the CNSN data were used. The resulting depths of the relocated hypocentres when using both CNSN and USTA data sets changed slightly as follows:

- The use of V1 shows that the relocated events shifted slightly toward shallower depths about 0.1 km and 0.2 km along the longitude and latitude directions, respectively (Figure 5.9(a)).
- With V2, the relocated focal depths displayed more changes when a denser network was used. Overall, events shifted toward shallower depths, with maximum depth differences of about 1 km along the longitude and about 0.1 km along the latitude (Figure 5.9(b)).
- With V3, variable differences in depths were observed along the longitude and latitude, an average of 0.5 km (Figure 5.9(c)). However, the relocated depths were more focused at 17 to 20 km when the combined data set was used.
- There was no remarkable change in depths when V4 and V5 were used (Figures 5.9(d) and 5.9(e)). Although V4 shows trivial differences between the relocated focal depths in both cases, the relocated epicentres revealed considerable differences using this model in both cases, which can be explained by relatively higher values of the velocities in this model.

Figure 5.9: Recalculated depths using only the CNSN data compared to using both CNSN and USTA data for five velocity models for Val-des-Bois event. The blue circles represent the recalculated depths resulted from only the CNSN data, and the relocated depths resulted from both of CNSN and USTA data for V1, V2, V3, V4 and V5 are shown by green squares (a), green-yellow diamonds (b), plus symbols (c), pink triangles (d) and purple stars (e), respectively.

The average relocated focal depths of Set #1 obtained using only the CNSN data and both the CNSN and USTA data sets are shown in Figure 5.10. The standard deviation indicators are also displayed in this figure. The values of the depth uncertainty measurements indicate slightly higher uncertainties when only the CNSN data were used. In general, it seems that the relocated focal depths when using both the CNSN and USTA data sets did not change remarkably, except for a slight shifting toward shallower depths, which were observed

when V2 and V3 were used. However, the results show reduced uncertainties when the combined data set was used.

Considering the hypocentre information obtained using the combined data set, it seems that there was a trade-off between epicentres and depths when V1 and V2 were used. The relocated hypocentres revealed that a slight shift toward shallower depths occurred when the combined data set was used. Also, events in northeastern parts were slightly shallower than those in other parts.

Figure 5.10: Average recalculated hypocentres projections of the Val-des-Bois aftershocks along the longitude (a) and latitude (b) directions. Use of both CNSN and USTA data are represented by black squares. Use of only the CNSN data are represented by blue circles. Standard deviations are shown by vertical lines.

5.2.1 Comparison of the Relocated Focal Depths of the Val-des-Bois Aftershocks through the VELEST and hypoDD Programs using CNSN+UATA Data

In the next step, the events in Set #1 were relocated through the JHD method using both the CNSN and USTA data sets. The resulting relocated depths were compared with the

results obtained by the DD method using V5 and those of the GSC catalog and are presented in Table 5.4. The comparisons of the results using the same velocity model but various methods are presented in Figure 5.11. The projections of the relocated hypocentres on vertical profiles along the longitude and latitude directions show that the obtained depths were slightly closer to the 18 km using the JHD method than with the DD method. However, the value of uncertainties increased when the DD method was applied.

Table 5.4: Comparison between recalculated depths obtained by VELEST and hypoDD programs (with V5) using both the CNSN and USTA data and those of the GSC catalog for the Val-des-Bois earthquake aftershocks. Cases with no obtained results are shown by “-”. *means focal depth was fixed.

Event #	Depth (km) in Catalog	Relocated depth (km)	
		VELEST	hypoDD (V5)
1	18.00*	18.36 ± 0.68	17.89 ± 0.18
2	18.00*	18.07 ± 0.05	-
3	18.00*	16.81 ± 0.16	-
4	18.00*	18.70 ± 0.18	-
5	20.40	21.82 ± 0.07	19.38 ± 1.40
6	18.00*	18.94 ± 0.16	-
7	18.00*	18.13 ± 0.04	-
8	18.00*	17.82 ± 0.69	19.16 ± 1.19
9	18.00*	18.15 ± 0.06	18.46 ± 0.49
10	18.00*	18.77 ± 0.25	-
11	18.00*	18.25 ± 0.08	18.83 ± 0.86
12	18.00*	18.36 ± 0.08	16.73 ± 1.23
13	18.00*	19.93 ± 0.14	18.38 ± 0.41
14	18.00*	18.83 ± 0.06	-
15	18.00*	17.01 ± 0.20	17.28 ± 0.72
16	18.00*	18.37 ± 0.59	18.75 ± 0.77
17	18.00*	28.02 ± 1.61	-
18	18.00*	20.96 ± 0.72	-
19	18.00*	18.01 ± 1.08	-

20	18.00*	17.87 ± 0.08	17.79 ± 0.18
21	18.00*	17.54 ± 0.08	-
22	18.00*	17.94 ± 0.10	-
23	18.00*	16.86 ± 0.25	16.83 ± 1.17
24	18.00*	17.53 ± 0.32	16.79 ± 1.18
25	18.00*	16.92 ± 0.35	-
26	18.00*	18.15 ± 0.28	-
27	18.00*	16.54 ± 0.19	-
28	18.00*	18.41 ± 0.24	17.62 ± 0.35
29	18.00*	15.36 ± 0.20	-
30	18.00*	17.24 ± 0.09	17.41 ± 0.56
31	18.00*	18.35 ± 0.25	20.05 ± 2.08
32	18.00*	16.08 ± 0.21	-
33	18.00*	19.89 ± 0.23	-
34	18.00*	15.85 ± 0.23	-
35	18.00*	19.97 ± 0.30	19.89 ± 1.90
36	18.00*	18.22 ± 0.68	17.78 ± 0.19
37	15.00	13.40 ± 0.27	-
38	18.00*	17.18 ± 0.54	18.18 ± 0.21
39	18.00*	18.54 ± 0.33	19.77 ± 1.79
40	18.00*	14.07 ± 0.50	-
41	18.00*	17.13 ± 0.21	-
42	18.00*	18.44 ± 0.81	-
43	18.00*	18.05 ± 0.08	-
44	18.00*	17.92 ± 0.06	-
45	18.00*	16.99 ± 0.16	-

The relocated focal depths using both CNSN and USTA data are compared with the results when using only the CNSN data in Figure 5.12. Based on these results, focal depths of events in Set #1 when using the combined data set through the JHD method were not remarkably changed and ranged from 16 and 20 km.

(a)

(b)

Figure 5.11: Comparisons between the recalculated hypocentres projection of the Val-des-Bois aftershocks obtained by the VELEST and hypoDD programs using both CNSN and USTA data and those in the GSC catalog (many of the catalog depths are fixed) along the longitude (a) and latitude (b) directions using MAXSEP = 5 km. The blue circles represent the GSC catalog hypocentres, and relocated hypocentres using the JHD and DD methods are presented by red pluses and dark triangles, respectively. Uncertainties obtained from output files are shown by vertical lines.

Figure 5.12: Recalculated hypocentre projections with the JHD method of the Val-des-Bois aftershocks along the longitude (a) and latitude (b) directions. Use of both CNSN and USTA data are represented by green stars, and use of only the CNSN data are represented by blue squares. Uncertainties are obtained from output files of the programs and are shown by vertical lines.

5.3 LADYSMITH AFTERSHOCKS USING ONLY THE CNSN DATA

The resulting focal depths using all velocity models and only the CNSN data in hypoDD for the Ladysmith earthquake aftershocks are presented in Table 5.5. The close stations distances to this event were 10, 16 and 59 km (at F55A, LSQ1 and VABQ stations, respectively). The differences between recalculated depths using the five velocity models and those of the GSC catalog are shown in Figure 5.13. It should be noted that some of the focal depths in the catalog were fixed depth. It can be seen that the maximum and minimum differences between the relocated and calculated depths were about 6.0 km in V4 (event 47) and about 0.01 km in V1 (event 33), respectively. The maximum and minimum average differences between the recalculated depths of Set #2 using the five velocity models and those of the GSC catalog were about 3.2 km (event 7) and 0.2 km (event 50), respectively.

Figure 5.14 displays the projections of the relocated hypocentres on vertical profiles along the longitude and latitude directions using all five velocity models and compares them with those of the GSC catalog. The results illustrate various changes in depths.

The average hypocentres of Set #2 obtained using only the CNSN data on vertical profiles along the longitude and latitude directions are presented in Figure 5.22.

Table 5.5: Comparison between recalculated depths in hypoDD (MAXSEP = 5 km) using only the CNSN data for five velocity models and those of the GSC catalog for Ladysmith earthquake aftershocks. Cases with no obtained results are shown by “-”. * means the focal depth was fixed.

Event #	Depth (km) in Catalog	Relocated depths (km) in hypoDD using only the CNSN data				
		V1	V2	V3	V4	V5
1	13.50	13.57 ± 0.09	14.68 ± 0.08	14.40 ± 0.23	15.58 ± 1.26	14.49 ± 0.06
2	14.00	13.82 ± 0.08	14.02 ± 0.11	13.58 ± 0.24	13.48 ± 1.46	14.05 ± 0.06
4	14.53	12.73 ± 0.37	12.68 ± 0.59	13.63 ± 0.94	13.37 ± 1.63	15.25 ± 1.89
5	12.00	12.00 ± 0.08	12.84 ± 1.93	10.19 ± 1.59	16.28 ± 4.42	13.67 ± 6.44
6	14.48	13.13 ± 0.15	13.71 ± 0.85	13.49 ± 0.65	9.00 ± 1.60	15.33 ± 0.26
7	9.91	13.43 ± 0.44	15.21 ± 6.25	10.63 ± 4.61	-	-
8	14.43	14.85 ± 0.09	16.38 ± 0.44	-	17.06 ± 1.33	15.67 ± 0.06
9	11.45	12.94 ± 0.18	13.18 ± 0.18	13.10 ± 0.48	14.63 ± 0.95	13.61 ± 0.07
10	13.96	13.73 ± 0.08	14.57 ± 0.08	14.33 ± 0.25	15.34 ± 1.32	14.48 ± 0.05
11	12.00*	12.53 ± 0.07	-	-	-	-
19	12.00*	12.60 ± 0.24	8.89 ± 2.96	14.66 ± 1.38	7.79 ± 3.95	12.03 ± 1.05
21	12.00*	-	-	-	-	-
26	12.00*	-	-	-	-	-
27	14.56	13.99 ± 0.06	15.08 ± 0.07	14.79 ± 0.31	15.90 ± 1.24	14.74 ± 0.06
32	12.00*	12.48 ± 0.10	13.63 ± 0.60	7.72 ± 1.17	9.88 ± 2.98	11.72 ± 0.87
33	13.50	13.50 ± 0.08	14.21 ± 0.10	13.72 ± 3.38	14.81 ± 1.27	14.49 ± 0.06
35	12.98	12.58 ± 0.08	13.04 ± 2.18	11.22 ± 0.23	-	13.17 ± 0.06
38	13.33	13.46 ± 0.07	13.99 ± 0.41	14.29 ± 0.25	14.21 ± 1.38	14.28 ± 0.06
39	13.19	12.74 ± 0.08	-	14.44 ± 0.27	12.55 ± 1.65	-
40	13.97	15.65 ± 0.35	15.56 ± 1.18	9.53 ± 3.71	-	-
42	13.46	13.04 ± 0.08	15.24 ± 0.08	14.56 ± 0.28	14.09 ± 1.40	14.21 ± 0.06
43	12.00*	11.62 ± 0.90	14.33 ± 1.67	10.39 ± 0.34	15.90 ± 1.46	12.42 ± 0.08
44	18.00	16.76 ± 0.17	17.70 ± 1.59	17.79 ± 0.50	22.59 ± 0.67	17.28 ± 0.16
45	18.00	17.48 ± 0.24	16.25 ± 0.12	17.78 ± 0.41	13.84 ± 1.67	17.59 ± 0.18
46	18.00	17.14 ± 0.19	17.66 ± 0.43	16.53 ± 0.52	19.08 ± 0.70	17.41 ± 0.17
47	18.00	22.84 ± 1.48	18.30 ± 0.56	20.38 ± 1.08	24.07 ± 1.29	18.75 ± 9.79
50	14.50	-	-	14.30 ± 0.28	-	-

Figure 5.13: Depth differences between the GSC catalog and relocated Ladysmith aftershocks using only the CNSN data for five different velocity models. The differences between recalculated depths obtained from V1, V2, V3, V4 and V5 and depths in the catalog are represented by squares, diamonds, upward triangles, downward triangles and oblique crosses, respectively. Uncertainties for all points, obtained from the output files of the hypoDD program are shown by vertical lines.

Figure 5.14: Comparisons between recalculated hypocentres projection of Ladysmith aftershocks using only the CNSN data with those of the GSC catalog (some of the catalog depths are fixed), along the longitude (a) and latitude (b) directions using MAXSEP =5 km and five velocity models. The blue circles represent the GSC catalog hypocentres, and relocated hypocentres using V1, V2, V3, V4 and V5 are shown by grey stars, green-yellow diamonds, black plus symbols, pink triangles and brown stars, respectively. Standard deviations are shown with vertical lines.

5.3.1 Comparison of the Relocated Focal Depths of the Ladysmith Aftershocks through the VELEST and hypoDD Programs using only the CNSN Data

The events in Set #2 were relocated using the JHD method through the VELEST program using only the CNSN data. The resulting relocated focal depths were compared with the results obtained with the DD method through the hypoDD program using V5 and are presented in Table 5.6. Figure 5.15 displays the projections of the relocated hypocentres on vertical profiles along the longitude and latitude directions using the JHD method and compares them with results obtained through the DD method and those of the GSC catalog. The comparison of the results using the same velocity model but various methods illustrated slight changes in depths. The values of uncertainty decreased when the JHD method was applied.

Table 5.6: Comparison between recalculated depths obtained by VELEST and hypoDD (V5) using only the CNSN data and those of the GSC catalog for the Ladysmith earthquake aftershocks. Cases with no obtained results are shown by “-”. *means focal depth was fixed.

Event #	Depth (km) in Catalog	Relocated depth (km)	
		VELEST	hypoDD (V5)
1	13.50	12.94 ± 0.66	14.49 ± 0.06
2	14.00	18.52 ± 0.84	14.05 ± 0.06
3	12.00	12.82 ± 0.08	-
4	14.53	14.10 ± 0.31	15.25 ± 1.89
5	12.00	15.50 ± 0.58	13.67 ± 6.44
6	14.48	15.19 ± 0.47	15.33 ± 0.26
7	9.91	13.69 ± 0.46	-
8	14.43	15.60 ± 0.29	15.67 ± 0.06
9	11.45	15.75 ± 0.15	13.61 ± 0.07
10	13.96	14.80 ± 0.44	14.48 ± 0.05
11	12.00*	13.86 ± 0.14	-
12	12.00*	15.36 ± 0.09	-
13	12.00*	-0.10 ± 0.02	-
14	12.00*	15.44 ± 0.07	-
15	12.00*	13.17 ± 0.09	-

16	12.00*	15.99 ± 3.42	-
17	12.00*	14.18 ± 0.10	-
18	12.00*	14.44 ± 0.08	-
19	12.00*	15.47 ± 0.10	12.03 ± 1.05
20	12.00*	9.81 ± 0.61	-
21	12.00*	15.52 ± 0.17	-
22	12.00*	14.84 ± 0.15	-
23	12.00*	15.17 ± 0.12	-
24	12.00*	13.91 ± 0.09	-
25	12.00*	13.68 ± 0.09	-
26	12.00*	14.56 ± 0.19	-
27	14.56	14.38 ± 0.75	14.74 ± 0.06
28	12.00*	15.26 ± 0.23	-
29	12.00*	13.19 ± 0.14	-
30	12.00*	13.63 ± 0.11	-
31	12.00*	14.33 ± 0.11	-
32	12.00*	14.05 ± 0.20	11.72 ± 0.87
33	13.50	14.83 ± 0.36	14.49 ± 0.06
34	12.00*	14.02 ± 0.07	-
35	12.98	15.25 ± 0.47	13.17 ± 0.06
36	12.00*	15.17 ± 0.43	-
37	12.00*	2.65 ± 0.30	-
38	13.33	15.87 ± 0.20	14.28 ± 0.06
39	13.19	15.41 ± 0.21	-
40	13.97	15.28 ± 0.43	-
41	12.00*	15.22 ± 0.33	-
42	13.46	15.21 ± 0.38	14.21 ± 0.06
43	12.00*	12.58 ± 0.18	12.42 ± 0.08
44	18.00	16.95 ± 0.42	17.28 ± 0.16
45	18.00	18.10 ± 0.66	17.59 ± 0.18
46	18.00	17.20 ± 0.48	17.41 ± 0.17
47	18.00	14.37 ± 0.23	18.75 ± 9.79
48	18.00	17.38 ± 0.22	-
49	18.00	17.66 ± 0.25	-
50	14.50	18.96 ± 0.24	-

Figure 5.15: Comparisons between recalculated hypocentre projections of the Ladysmith aftershocks obtained by VELEST and hypoDD programs using only the CNSN data and those in the GSC catalog (many of the catalog depths are fixed) along the longitude (a) and latitude (b) directions using $\text{MAXSEP} = 5$ km. The blue circles represent the GSC catalog hypocentres, and relocated hypocentres using the JHD and DD methods are represented by red pluses and dark triangles, respectively. Uncertainties obtained from output files are shown by vertical lines.

5.4 LADYSMITH AFTERSHOCKS USING CNSN AND USTA DATA

In the next step, focal depths for Set #2 using all five velocity models and both CNSN and USTA data sets in hypoDD were calculated and are presented in Table 5.7. The differences between the recalculated depths using the five velocity models and those of the GSC catalog are shown in Figure 5.16. It can be seen that most of the relocated depths were deeper than those of the GSC catalog. The maximum and minimum differences in the relocated depths were about 10 km (event 21) and about 0.01 km (event 27), respectively.

The average depth differences between the recalculated depths of Set #2 and those of the GSC catalog were relatively lower than those using only the CNSN data. It should be mentioned that some of the USTA data were used in the GSC catalog. These lower differences were associated with lower uncertainties and sufficiently dense station coverage within close epicentral distances to the focal depth. The station network geometry, the accuracy of phase arrival times and the structure of velocity model are possible reasons for uncertainties. The maximum and minimum average differences were about 2.9 km (event 50) and 0.03 km (event 2), respectively. These results suggest that adequate station coverage can reduce the errors in the determination of seismic events depths and provide more realistic estimations of focal depths.

Table 5.7: Comparison between recalculated depths in hypoDD (MAXSEP=5 km) using both CNSN and USTA data for five velocity models and those of the GSC catalog for the Ladysmith earthquake. Cases with no obtained results are shown by “-”. * means the focal depth was fixed.

Event #	Depth (km) in Catalog	Relocated depth (km) in hypoDD using CNSN + USTA data				
		V1	V2	V3	V4	V5
1	13.50	14.07 ± 0.03	14.23 ± 0.03	13.84 ± 0.13	16.23 ± 1.44	14.61 ± 0.04
2	14.00	13.67 ± 0.02	13.79 ± 0.02	13.31 ± 0.13	15.21 ± 1.48	14.17 ± 0.04
4	14.53	14.76 ± 0.02	15.47 ± 0.03	14.60 ± 0.33	16.73 ± 5.27	15.48 ± 0.04
5	12.00	12.74 ± 0.03	12.25 ± 0.06	12.44 ± 0.14	14.05 ± 1.54	12.91 ± 0.06
6	14.48	13.21 ± 0.05	13.13 ± 0.07	12.55 ± 0.13	13.84 ± 1.45	13.21 ± 0.04
7	9.91	11.38 ± 0.15	9.71 ± 0.28	10.53 ± 0.42	-	8.92 ± 0.61
8	14.43	14.64 ± 0.04	15.52 ± 0.04	14.57 ± 0.13	16.76 ± 1.50	15.37 ± 0.03
9	11.45	12.78 ± 0.04	12.13 ± 0.06	12.36 ± 0.14	13.69 ± 4.66	13.00 ± 0.05
10	13.96	13.89 ± 0.02	14.13 ± 0.03	13.45 ± 0.13	15.44 ± 1.48	14.33 ± 0.04
11	12.00*	12.43 ± 0.05	12.39 ± 0.06	10.86 ± 0.06	14.28 ± 1.57	12.24 ± 0.12
19	12.00*	13.07 ± 0.03	13.77 ± 0.05	13.27 ± 0.12	15.26 ± 1.45	13.91 ± 0.03
21	12.00*	12.68 ± 0.10	12.66 ± 0.08	11.86 ± 0.34	22.98 ± 0.84	11.19 ± 0.67
26	12.00*	11.30 ± 0.41	12.78 ± 0.17	-	-	10.98 ± 0.39
27	14.56	13.86 ± 0.04	13.96 ± 0.04	13.26 ± 0.13	15.12 ± 1.45	14.58 ± 0.04
32	12.00*	12.73 ± 0.07	12.85 ± 0.07	12.56 ± 0.13	14.61 ± 1.57	13.13 ± 0.08
33	13.50	13.62 ± 0.02	13.68 ± 0.04	13.25 ± 0.13	15.22 ± 1.51	14.16 ± 0.04
35	12.98	13.47 ± 0.05	13.95 ± 0.05	13.48 ± 0.13	15.33 ± 1.47	13.68 ± 0.13
38	13.33	13.48 ± 0.03	13.56 ± 0.05	13.24 ± 0.13	15.08 ± 1.52	13.99 ± 0.04
39	13.19	13.23 ± 0.04	13.05 ± 0.06	12.86 ± 0.13	14.94 ± 1.57	13.48 ± 0.12
40	13.97	11.55 ± 0.10	13.41 ± 0.27	9.58 ± 0.83	-	10.81 ± 0.40
42	13.46	13.66 ± 0.04	13.73 ± 0.05	13.39 ± 0.13	15.18 ± 1.49	14.04 ± 0.04
43	12.00*	12.13 ± 0.05	12.57 ± 0.08	12.38 ± 0.14	14.68 ± 0.40	13.06 ± 0.04
44	18.00	17.01 ± 0.07	17.34 ± 0.10	16.48 ± 0.19	13.75 ± 0.50	16.69 ± 0.16
45	18.00	17.75 ± 0.06	16.03 ± 0.07	18.86 ± 3.00	16.24 ± 1.37	16.62 ± 0.27
46	18.00	16.77 ± 0.05	17.80 ± 0.05	16.14 ± 0.19	5.55 ± 0.35	16.89 ± 0.13
47	18.00	17.98 ± 0.42	19.51 ± 0.16	18.67 ± 4.58	1.71 ± 1.26	18.60 ± 0.33
50	14.50	13.92 ± 0.09	8.37 ± 0.48	12.40 ± 0.31	-	11.73 ± 0.18

Figure 5.16: Depth differences between the GSC catalog and relocated Ladysmith aftershocks using both CNSN and USTA data for five different velocity models. The differences between recalculated depths obtained from V1, V2, V3, V4 and V5 and depths in the catalog are represented by squares, diamonds, upward triangles, downward triangles and oblique crosses, respectively. Uncertainties for all points obtained from the output files of the hypoDD program are shown by vertical lines.

Figure 5.17 displays the projections of the relocated hypocentres of Set #2 on vertical profiles along the longitude and latitude directions.

The average relocated focal depths using both CNSN and USTA data sets were compared with the results using only the CNSN data and are shown in Figure 5.18. Based on these results, focal depths of events in Set #2 using combined data sets were more focused at a depth of ~15 km, ranging between 12 and 18 km.

Figure 5.17: Comparisons between recalculated hypocentre projections of the Ladysmith aftershocks along the longitude (a) and latitude (b) directions using $\text{MAXSEP} = 5$ km and five velocity models. The blue circles represent the GSC catalog hypocentres, and the relocated hypocentres using V1, V2, V3, V4 and V5 are represented by grey stars, green-yellow diamonds, black plus symbols, pink triangles and brown stars, respectively. Standard deviations are shown with vertical lines.

Figure 5.18: Average relocated focal depths of Set #2. The black dotted lines represent the use of both CNSN+USTA data, and the blue dashed lines represent the use of only the CNSN data. Standard deviations are shown with vertical lines.

The average depth differences from the GSC catalog when using both CNSN and USTA data sets were compared with the results using only the CNSN data and are shown in Figure 5.19. The values of the depth difference uncertainty measurements indicate relatively higher uncertainties when only the CNSN data were used compare to using both CNSN and USTA data sets.

Figure 5.19: Average depth differences of Set #2 from the GSC catalog. The black squares represent the use of both CNSN+USTA data, and the blue diamonds represent the use of only the CNSN data. Standard deviations are shown by vertical lines.

Figure 5.20 shows a 3D plot of the average resulting relocated hypocentres using both CNSN and USTA data sets compared to the results obtained by using only the CNSN data.

The relocated events revealed an almost northwest- southeast seismicity trend. It seems that events on the eastern side were relatively deeper than those on the western side, which can be interpreted as a northeastern dipping plane with a northwest striking direction. If it compares to the focal mechanism solution obtained in this study (see Section 6.1), the probable fault plane would be a 130° striking plane with a northeast-dipping of about 54° and a slip of about 59° .

The dominant seismogenic layer where these aftershocks sequence occurred is located at a depth about 12 to 18 km which is compatible with most parts of the WQSZ and the thickness of this layer can be estimated about 3.0 km.

Figure 5.20: Three-dimensional plot of the average relocated hypocentres of the Ladysmith earthquake aftershocks. The relocated hypocentres obtained using both CNSN+USTA data are represented by solid blue circles, and results obtained using only the CNSN data are represented by the empty blue circles.

Figure 5.21 displays the projections of the relocated hypocentres on vertical profiles along the longitude and latitude directions using V1, V2, V3, V4 and V5. This figure shows the relocated depths when both the CNSN and USTA data sets were used and compares the results with the recalculated depths when only the CNSN data were used. The resulting depths of the relocated hypocentres using both the CNSN and USTA data sets changed slightly as follows:

- Use of V1 shows the relocated events slightly shifted toward shallower depths about 0.5 km along the longitude and latitude (Figure 5.21(a)).

- With V2, the relocated focal depths displayed more changes when a dense network was used. Overall, events with this model were systematically shifted toward shallower depths and the east. The maximum depth difference was about 1 km along the longitude and about 0.5 km along the latitude (Figure 5.21(b)).
- With V3, variable differences were observed at depths of about 1 km along the longitude and about 0.7 km along the latitude (Figure 5.21(c)).
- There were no considerable change in depths when V4 was used (Figure 5.21(d)).
- With V5, the depths decreased about 1 km along the longitude and latitude (Figure 5.21(e)).

Considering the hypocentre information obtained using the combined data set, it seems that there was a trade-off between epicentres and depths when V1 and V5 were used. The relocated hypocentres revealed a slight shift toward shallower depths occurred when the combined data set was used. Also, events in southwestern parts were slightly shallower than those in the other parts.

Figure 5.21: Recalculated depths using only the CNSN data in comparison with using both CNSN + USTA data for five velocity models for the Ladysmith event. The blue circles represent the recalculated depths resulted from only the CNSN data, and the relocated depths resulted from both CNSN and USTA data for V1, V2, V3, V4 and V5 are represented by green squares (a), green-yellow diamonds (b), plus symbols (c), pink triangles (d) and purple stars (e), respectively.

The average relocated focal depths of Set #2 obtained using only the CNSN data and both the CNSN and USTA data sets are shown in Figure 5.22. The standard deviation indicators are also displayed in this figure. The values of the depth uncertainty measurements indicate slightly higher uncertainty when only the CNSN data were used compare using both CNSN and USTA data. In general, it seems that the relocated focal depths when using both CNSN and USTA data were not remarkably changed, except for a slight shifting toward shallower depths, which was observed when V2 and V5 were used. However, the results showed less

uncertainty when the combined data set was used compare to those obtained using only the CNSN data.

Figure 5.22: Average recalculated hypocentre projections of Ladysmith aftershocks along the longitude (a) and latitude (b) directions. Use of both CNSN and USTA data are represented by black squares, and use of only the CNSN data are represented by blue circles. Standard deviations are shown by vertical lines.

5.4.1 Comparison of the Relocated Focal Depths of the Ladysmith Aftershocks through the VELEST and hypoDD Programs using CNSN+UATA Data

In the next step, the events in Set #2 were relocated through the JHD method using both the CNSN and USTA data sets. The resulting relocated depths were compared with the results obtained by the DD method using V5 and those of the GSC catalog and are presented in Table 5.8.

The comparisons of the results using the same velocity model but various methods are presented in Figure 5.23. The projections of the relocated hypocentres on vertical profiles along the longitude and latitude directions show that the depths obtained by the JHD method were slightly deeper than the results obtained by the DD method. However, the values of uncertainties increased when the JHD method was applied.

Table 5.8: Comparison between recalculated depths obtained by VELEST and hypoDD (V5) using both the CNSN and USTA data and those of the GSC catalog for the Ladysmith earthquake aftershocks. Cases with no obtained results are shown by “-”. *means focal depth was fixed.

Event #	Depth (km) in Catalog	Relocated depth (km)	
		VELEST	hypoDD (V5)
1	13.50	13.41 ± 0.84	14.61 ± 0.04
2	14.00	16.77 ± 0.80	14.17 ± 0.04
3	12.00	15.96 ± 0.86	-
4	14.53	16.92 ± 3.06	15.48 ± 0.04
5	12.00	15.46 ± 0.51	12.91 ± 0.06
6	14.48	5.76 ± 1.08	13.21 ± 0.04
7	9.91	13.32 ± 0.39	8.92 ± 0.61
8	14.43	15.49 ± 0.35	15.37 ± 0.03
9	11.45	14.92 ± 0.20	13.00 ± 0.05
10	13.96	14.95 ± 0.73	14.33 ± 0.04
11	12.00*	14.59 ± 0.23	12.24 ± 0.12
12	12.00*	15.25 ± 0.65	-
13	12.00*	0.66 ± 0.09	-

14	12.00*	15.38 ± 0.08	-
15	12.00*	9.00 ± 0.56	-
16	12.00*	15.59 ± 2.99	-
17	12.00*	14.84 ± 0.43	-
18	12.00*	14.64 ± 0.14	-
19	12.00*	15.62 ± 0.16	13.91 ± 0.03
20	12.00*	9.32 ± 0.70	-
21	12.00*	15.41 ± 0.17	11.19 ± 0.67
22	12.00*	16.26 ± 0.37	-
23	12.00*	14.80 ± 0.17	-
24	12.00*	14.67 ± 0.14	-
25	12.00*	13.82 ± 0.12	-
26	12.00*	14.16 ± 0.34	10.98 ± 0.39
27	14.56	11.50 ± 0.95	14.58 ± 0.04
28	12.00*	16.67 ± 0.31	-
29	12.00*	12.80 ± 0.29	-
30	12.00*	13.42 ± 0.12	-
31	12.00*	13.89 ± 0.20	-
32	12.00*	13.99 ± 0.18	13.13 ± 0.08
33	13.50	15.04 ± 0.66	14.16 ± 0.04
34	12.00*	14.17 ± 0.16	-
35	12.98	14.73 ± 0.44	13.68 ± 0.13
36	12.00*	14.21 ± 0.43	-
37	12.00*	10.54 ± 1.58	-
38	13.33	15.46 ± 1.89	13.99 ± 0.04
39	13.19	15.00 ± 0.26	13.48 ± 0.12
40	13.97	14.42 ± 0.67	10.81 ± 0.40
41	12.00*	13.24 ± 0.33	-
42	13.46	14.32 ± 0.36	14.04 ± 0.04
43	12.00*	10.15 ± 0.66	13.06 ± 0.04
44	18.00	17.10 ± 0.70	16.69 ± 0.16
45	18.00	16.33 ± 0.62	16.62 ± 0.27
46	18.00	15.89 ± 0.43	16.89 ± 0.13
47	18.00	14.77 ± 0.28	18.60 ± 0.33
48	18.00	15.80 ± 1.03	-
49	18.00	22.81 ± 2.15	-
50	14.50	22.52 ± 0.76	11.73 ± 0.18

(a)

(b)

Figure 5.23: Comparisons between the recalculated hypocentre projections of the Ladysmith aftershocks obtained by VELEST and hypoDD using both CNSN and USTA data and those in the GSC catalog (many of the catalog depths are fixed) along the longitude (a) and latitude (b) directions using MAXSEP = 5 km. The blue circles represent the GSC catalog hypocentres and relocated hypocentres using the JHD and DD methods are represented by red pluses and dark triangles, respectively. Uncertainties obtained from output files are shown by vertical lines.

The relocated focal depths in case of using both the CNSN and USTA data sets were compared with results using only the CNSN data and are shown in Figure 5.24. Based on these results, the focal depths of events in Set #2 using the combined data set through the JHD method were not remarkably changed and ranged from 13 and 16 km.

Figure 5.24: Recalculated hypocentre projections of the Ladysmith aftershocks along the longitude (a) and latitude (b) directions with the JHD method. The use of both CNSN and USTA data are represented by green stars, and the use of only the CNSN data are represented by blue squares. Uncertainties are obtained from output files of the programs and shown by vertical lines.

5.5 EIGHTEEN EVENTS USING ONLY THE GSC' S CATALOG DATA

Focal depths of 18 events in Set #3 were extracted from the GSC catalog (Figure 5.25).

The focal depths for some of these events were routinely assigned a fixed depth of 18 km (mid-crustal point) (Basham et al., 1979), which is related to the spread out condition of the seismic stations, and uncertainties (indicated by bold numbers in Table 5.9). It should be noted that some of the USTA data (especially if the events occurred after the Ladysmith earthquake) and also data from the New England Seismic Network were used in the catalog locations.

Table 5.9: Focal depths of Set #3 available in the GSC catalog, when only the CNSN data is used. Bold numbers represent fixed depths.

Earthquake	Date	Mag	Catalog
1	2013/01/16-A	3.5	21.00
2	2013/01/16-B	3.0	18.00
3	2013/04/15	3.1	12.80
4	2013/05/17-A	5.2	13.50
5	2013/05/17-B	4.1	14.00
6	2013/05/17-C	3.2	14.00
7	2013/05/21	3.4	18.00
8	2013/05/24	3.6	18.00
9	2013/05/30	3.7	13.00
10	2013/06/30	3.1	14.00
11	2013/09/04	3.1	18.00
12	2013/10/20	3.6	18.00
13	2014/02/07	3.1	12.50
14	2014/03/30	3.0	18.00
15	2014/07/04	3.0	18.00
16	2015/04/04	3.0	18.00
17	2015/04/20	3.8	14.50
18	2015/07/07	3.2	18.00

Figure 5.25: Focal depths extracted from the GSC catalog. The columns with darker color show fixed depths.

5.6 EIGHTEEN EVENTS USING CNSN AND USTA DATA

In next step, the travel times method (using the DAN3 program) was applied to relocate focal depths for 18 events in Set #3 using both CNSN and USTA data. The focal depths were calculated in two phases. The focal depths were first determined using all seismic stations and included CNSN and USTA data. The primary (P) and secondary (S) wave travel times were used to determine the free depths using the velocity model of Brune and Dorman (1963). In the calculation of the hypocentral locations, variable sets of seismic stations were used. These various stations had different geographical distributions and varied underlying velocity structures (Figure 5.26). Consequently, these factors can possibly produce high scattering in the resulting hypocentres.

In order to eliminate the effect of these variations in regional velocity, the next step was the iteration of all processes using only the three closest stations' data sets; and, the earthquakes hypocentres were calculated using only the Pg and Sg phases (Pg and Sg are direct crustal phases) from those three closest stations to the epicentre of each event.

The resulting calculated depths (using both CNSN and USTA data) were compared to each other and to those of the GSC catalog when available. The depths from the various data sets were mostly similar and are presented in Table 5.10.

Table 5.10: Relocated focal depths of Set #3. Bold numbers represent fixed depths and italic numbers represent when one or more of three closest stations were the USTA stations and used in depth calculations.

			Free Depths (km)		
				Recalculated Depths Using	
Earthquake	Date	Mag	Catalog	All Stations (CNSN+USTA)	3 closest Stations
1	2013/01/16-A	3.5	21.00	18.09 ± 0.42	18.06 ± 0.22
2	2013/01/16-B	3.0	18.00	18.70 ± 1.88	17.01 ± 0.10
3	2013/04/15	3.1	12.80	8.67 ± 0.91	8.88 ± 0.21
4	2013/05/17-A	5.2	13.50	12.73 ± 0.49	<i>12.97 ± 0.22</i>
5	2013/05/17-B	4.1	14.00	13.55 ± 0.37	<i>15.90 ± 0.18</i>
6	2013/05/17-C	3.2	14.00	13.14 ± 0.46	<i>13.88 ± 0.20</i>
7	2013/05/21	3.4	18.00	17.74 ± 0.45	15.67 ± 0.60
8	2013/05/24	3.6	18.00	17.14 ± 0.73	<i>17.44 ± 0.42</i>
9	2013/05/30	3.7	13.00	12.89 ± 0.24	<i>11.98 ± 0.10</i>
10	2013/06/30	3.1	14.00	13.85 ± 0.34	<i>13.78 ± 0.15</i>
11	2013/09/04	3.1	18.00	15.58 ± 0.49	<i>22.05 ± 0.60</i>
12	2013/10/20	3.6	18.00	20.34 ± 0.47	<i>18.81 ± 1.30</i>
13	2014/02/07	3.1	12.50	12.19 ± 1.37	<i>16.89 ± 0.33</i>
14	2014/03/30	3.0	18.00	18.57 ± 0.44	<i>16.70 ± 0.05</i>
15	2014/07/04	3.0	18.00	19.48 ± 0.63	<i>16.78 ± 0.48</i>
16	2015/04/04	3.0	18.00	18.46 ± 0.41	<i>17.40 ± 0.12</i>
17	2015/04/20	3.8	14.50	14.79 ± 0.88	<i>20.47 ± 0.36</i>
18	2015/07/07	3.2	18.00	16.50 ± 0.47	17.28 ± 0.21

Figure 5.26: Event 20130530, which has been selected as an example, is represented by the star, and the diamonds and square represent the three closest stations to the event. The arrow indicates the movement of this earthquake from its location in the catalog to the location obtained by the three closest stations.

Gomberg et al., (1990) suggested that in order to determine reliable focal depth, records at close epicentral distances (within about 1.4 times the focal depth) are required. Therefore, taking advantage of the USTA data allowed us to calculate more reliable depths for events with fixed depths. Also, one or more of the three closest stations used in many of the recalculated depths (more than 70%) (indicated by italic numbers in Table 5.10) were from the USTA, which enabled us to calculate more accurate depths. Figure 5.27 displays a comparison between recalculated focal depths of Set #3 using the catalog data and the combined CNSN and USTA data sets.

Figure 5.27: Estimated focal depths using data from all possible seismic stations (both CNSN and USTA) (shown in black), using the three closest stations (shown in yellow-green) obtained with the travel times method using the DAN program and focal depths from the GSC catalog (shown in grey) for comparison purposes.

The calculated focal depths using the three closest stations exhibited more differences from the free depths in the catalog than those depths calculated from all stations (Figure 5.28). The maximum and minimum depth differences from the catalog were about 6.0 km obtained from the three closest stations (event 17) and about 0.10 km obtained from all stations data (event 9), respectively.

Figure 5.28: Differences between the calculated focal depths in this study and focal depths of events with free depths in the GSC catalog. Estimated focal depth differences using data from all possible seismic stations (both CNSN and USTA) are shown in black and using the three closest stations are shown in yellow-green.

The focal depths range from 9 to 21 km in both cases (Figure 5.29), corresponding to shallow to mid-crustal depths, which is typical of the WQSZ (Bent and Perry, 2002; Ma and Atkinson, 2006; Bent et al., 2015). More reliable focal depths were obtained using the denser seismic network, due to the addition of the USTA data and provision of closer stations.

Figure 5.29: Comparison of focal depths of Set #3 using both CNSN+USTA data (shown by black squares) and the GSC catalog data (shown by blue circles). Standard deviations are shown by vertical lines.

It was found that different combinations of stations provided almost similar results. The relocated focal depths for five aftershocks of the Ladysmith earthquake, obtained from different methods (standard travel time inversion, DD and JHD methods), were compared; and, the results are shown in Table 5.11. The resulting hypocentres from different methods with the same velocity model (DD technique using V5 and JHD method) were compared. It is worth noting that some of the USTA data (e.g. F55A station) were used in the catalog depths of these events. The calculated results were in some agreement with each other, and with the typical focal depth for the region.

Table 5.11: Comparison between recalculated depths of the Ladysmith aftershocks obtained from three different ways. * means depth has been calculated using free depth, **means depth has been calculated using RDPM (Regional Depth Phase Modelling).

Event no.	Date	Mag (M _N)	Catalog	Free Depths (km)				
				Standard Travel Time Inversion		Double-Difference		Joint-Hypocentre-Determination (velest)
				All Stations	3 closest Stations	(V1)	(V5)	
4	2013/05/17-A	5.2	13.57*, 13.50**	12.73	12.97	14.07	14.61	13.41
5	2013/05/17-B	4.1	14.02*, 14.00**	13.55	15.90	13.67	14.17	16.77
6	2013/05/17-C	3.2	14.00	13.14	13.88	13.89	14.33	14.95
9	2013/05/30	3.7	12.97*, 13.50**	12.89	11.98	13.62	14.16	15.04
10	2013/06/30	3.1	14.00	13.85	13.78	11.46	10.81	14.42

Although obtaining reliable hypocentres could increase our knowledge about seismic hazard analysis and seismotectonic research, improvement of the focal depths by a few kilometres may not be very effective from an engineering point of view, because the measurement of the shear wave velocity only down to 30 m (Vs30) is recommended as an initial factor to determine the seismic shaking level.

6. FOCAL MECHANISM

Determination of the focal mechanisms of earthquakes is one of the most important pursuits in seismotectonic investigations. Some noteworthy information can be obtained by the focal mechanisms such as the slip direction in earthquakes, and the fault nature and orientation of stress fields (McKenzie, 1969; Wahlstrom, 1987).

One of the main reasons for undertaking this study was to determine whether the additional US Transportable Array (USTA) data would result in a superior constrained focal mechanism solution or to obtain well-constrained solutions for small earthquakes (magnitudes of 3 to 4) or make any difference between solutions obtained by denser network data and those solutions obtained data of the current network.

This part of the study covers 30 events that occurred during 2013 through 2015, including events in Set #3 and 12 additional more events (that mostly occurred from July 2015 to the end of 2015), which include small earthquakes through the deployment of the USTA in the Western Quebec Seismic Zone (WQSZ). In view of the fact that the polarities of the small earthquakes may not have been clear enough and, therefore, their focal mechanism solutions not be reliably determined, this group of events was chosen to investigate any possible advantages in the determination of focal mechanisms using data from a denser network.

In order to determine the focal mechanisms, primary (P) wave polarities and the FOCMEC program (Snoke et al., 1984), as detailed in Chapter 3, Section 3.5, were utilized, and focal mechanisms were determined. These mechanisms showed thrust or thrust/strike-slip faulting, and most of their solutions had a nodal plane dipping about 40° to 50° in the NE direction, which is the dominant pattern of faulting in this region (Wahlstrom, 1987; Adams

et al., 1988, 1989; Adams, 1991; Adams and Basham, 1991; Bent, 1996a, 1996b; Bent and Perry, 1999; Bent et al., 1999; Bent and Drysdale, 2000; Bent et al., 2003; Bent et al., 2015).

6.1 FOCAL MECHANISM SOLUTION USING CNSN AND USTA DATA

Focal mechanisms for the 30 events are evaluated using both Canadian National Seismograph Network (CNSN) and USTA data in the FOCMEC program. In order to get acceptable solutions, several trials were done based on changing the allowed P polarity errors and the increment for the trend and plunge of the B axis (the intermediate stress axis or intersection of the nodal planes) and the angle of the A axis (axis of a double couple point source). The best solution of each event was selected.

Figure 6.1 shows the examples of obtained solutions for two of the studied events. These solutions include the strike (the azimuth of the fault plane intersection and a horizontal surface relative to north), the dip (the vertical angle between the fault plane and Earth's surface), the rake (the movement direction of the hanging wall during rapture), the trend (the direction of the axes) and the plunge (the vertical angle between the axes and Earth's surface). The full documentation of focal mechanisms with all possible solutions and the polarity data used for the determinations are presented in Appendix B. A summary of the final single solution for the analyzed earthquakes in this study are given in Tables 6.1 and 6.2.

Figure 6.1: Two examples of focal mechanism solutions using both CNSN and USTA data

Table 6.1 lists the strike, dip and rake for seventeen events that show well constrained mechanisms. In most cases, the solutions were similar; therefore, the closest to mean was used as the preferred solution.

Table 6.1: Well constrained focal mechanism solutions obtained by using both CNSN and USTA data

Date	Plane 1			Plane 2			P - axis		T - axis		B - axis	
	Strike (°)	Dip (°)	Rake (°)	Strike (°)	Dip (°)	Rake (°)	Trend (°)	Plunge (°)	Trend (°)	Plunge (°)	Trend (°)	Plunge (°)
20130116-A	304	52	51	177	52	129	241	0	151	60	331	30
20130116-B	316	59	60	183	42	129	67	9	175	63	332	25
20130517-A	130	54	59	356	46	126	242	5	341	65	150	25
20130517-B	138	50	57	3	50	123	71	0	341	65	161	25
20130517-C	140	25	90	320	65	90	50	20	230	70	140	0
20130524	6	13	51	226	80	98	309	35	146	54	44	8
20130904	117	62	-11	212	80	-152	78	36	337	16	227	50
20131020	242	56	78	82	36	107	340	10	114	76	248	10
20140207	161	78	78	28	17	136	261	32	55	55	163	12
20140704	77	52	-20	180	74	-141	45	39	304	14	198	48
20150404	274	63	61	144	38	133	25	14	140	61	288	25
20150420	285	48	-19	28	76	-137	241	55	331	0	61	35
20150707	347	21	44	215	75	105	292	29	145	57	31	15
20150715	317	55	65	175	42	121	64	7	171	69	331	20
20150727	212	61	78	55	31	109	310	15	95	72	218	10
20150805	44	38	-47	175	63	-118	41	61	285	14	188	25
20150817	10	47	62	288	49	117	299	1	207	70	30	20

The polarities of the events with small magnitudes may not have been clear at all stations; unclear polarities were not used. Table 6.2 presents trend and plunge of P, T and B axes for undefined focal mechanism solutions for thirteen events.

With regards to the rake, seven of these events were likely due to thrust faulting (20130415, 20130530, 20130630, 20140330, 20150909, 20151020-A and 20151020-B); and, six events (20130521, 20150502, 20150726, 20150830, 20151008 and 20151128) could have been strike-slip or thrust, but the accurate orientation of their nodal planes could not be defined. However, the trend of the P axis (the maximum compression direction), T axis (the maximum tension direction) and B axes for some of these events are relatively defined, and the results are displayed in the Table 6.2. The undetermined solutions are displayed as “?” in Figure 6.2.

Table 6.2: Trend and plunge of P, T and B axes for undefined focal mechanism solutions using both CNSN and USTA data

Date	Nodal planes	P – axis		T - axis		B -axis	
		Trend	Plunge °	Trend	Plunge °	Trend	Plunge °
20130415	cannot be determined	is not well determined, solutions are dispersed mainly in SW and some in SE, NE quadrants	undetermined	is not well determined, solutions are dispersed in NNW octant, some in SE, NNE quadrants	approximately 40° (moderate)	is not well determined, solutions are dispersed mainly in SE and some in SW quadrants	approximately 10°-25° (shallow to moderate)
20130521	cannot be determined	is not well determined, solutions are dispersed in every azimuth but SE ruled out	undetermined	is not well determined, the solutions are dispersed mainly in east hemisphere and some in NW quadrant	moderate, approximately 45°- 55° (horizontal in NW)	is not well determined, solutions are dispersed in every azimuth but NW ruled out	nearly horizontal

20130530	cannot be determined	is not well determined, solutions are dispersed in ENE and ESE octants and SW quadrants	approximately 0°- 30° (shallow to moderate)	is not well determined, nearly in every azimuth	near vertical	is not well determined, solutions are dispersed in NNW, SSE octants, some in NE, SW quadrants	approximately 0°-35° (shallow to moderate)
20130630	cannot be determined	solutions are dispersed in SE and NW quadrants	approximately 0°-20° (near horizontal)	is not well determined, solutions are dispersed in NNE, SSW, NNW octants	approximately 65°- 90° (near vertical)	is not well determined, solutions are mainly dispersed in NNE, some solutions in SW, NNW	undetermined (shallow to moderate in SW)
20140330	cannot be determined	is not well determined, solutions are in SW and NE quadrants	not well determined (probably shallow to moderate)	is not well determined, solutions are mainly dispersed in ESE , ENE, some in NW	approximately 45°-65° (near moderate)	is not well determined, solutions are mainly dispersed in NW and some in SE quadrants	not well determined (probably moderate)
20150502	cannot be determined	solutions are in SE quadrant	approximately 45°- 90° (moderate to vertical)	solutions in NW quadrant	horizontal in NW, approximately 0°-40° (shallow to moderate) in SW	is estimated mainly horizontal	approximately 15°- 40°
20150726	cannot be determined	solutions are mainly dispersed in NE, some solutions in NW quadrant	moderate	solutions are mainly in SW	is not well determined , near moderate	solutions in NW and SE and some in NE quadrants	approximately horizontal to moderate (0°-40°)
20150830	cannot be determined	solutions are dispersed in SW quadrant	approximately 35°- 90° (moderate to vertical)	solutions are mainly dispersed in NE and some solutions in ESE quadrants	approximately 10°- 45° (shallow to moderate)	solutions are dispersed in NW, SE and WNE quadrants	approximately 0°- 50° (shallow to moderate)
20150909	cannot be determined	is not well determined, solutions are mainly dispersed in NW, SE and some in NE quadrants	nearly horizontal in SE and NE, horizontal to moderate in NW quadrant	solutions are in ENE and ESE octants	near vertical to moderate	is not well determined, solutions are mainly dispersed in SW, NE quadrants and some in NWN octant	nearly horizontal in NE, shallow to moderate in SW quadrants and NWN octant

20151008	cannot be determined	solutions are mainly in SW and some in NE quadrants	is not well determined in SW, shallow to moderate in NE	solutions are mainly in NW and some in SE quadrants	is not well determined in NW, shallow to moderate in SE	is not well determined, nearly in every azimuth	is not well determined, (shallow to moderate)
20151020-A	cannot be determined	solutions are mainly in ESE and some in NE quadrants	approximately 0°- 30° (horizontal to moderate)	solutions are in NNW and some in NNE octants	nearly moderate	is not well determined, solutions are mainly dispersed in SW, SE and some in NW quadrants	approximately 10°- 45° (shallow to moderate)
20151020-B	cannot be determined	solutions are mainly in SE and some in ENE quadrants	is not well determined , shallow to moderate	solutions are mainly in SW quadrant and some in NNE octant	shallow to moderate	solutions are mainly dispersed in NW quadrant and some in ESE octant	shallow to moderate in NW, near horizontal in ESE
20151128	cannot be determined	solutions are dispersed in SW and SE quadrants	nearly moderate	solutions are dispersed in NW, SE quadrants	shallow to moderate, some nearly horizontal in NW and SE	solutions are mainly in NE, and some in NW	shallow to moderate

Figure 6.2 presents a map with the geographical distribution of the 30 focal mechanism solutions (the lower hemisphere beach-ball diagrams).

Figure 6.2: Pattern of focal mechanism solutions obtained using both CNSN and USTA data in the study area, the circled ? means that a well constrained solution could not be obtained (an undetermined solution); the compressional and dilatational quadrants in the beach balls are shown by red and white, respectively.

While seventeen of these solutions were well constrained, others had fairly large uncertainties. Nevertheless, seven of these seventeen solutions do suggest a pattern of thrust faulting on northwest striking planes (events 20130116-A, 20130116-B, 20130517-A, 20130517-B, 20130517-C, 20150404 and 20150715). The northwest trends of these events are in agreement with the Ottawa River trend. The P axes of these events are

identified by a near horizontal component and represent northeastern orientation, which is in accordance with the previous studies and also with the general P axes trend for eastern North America (Adams and Basham, 1991; Zoback, 1992; Adams, 1995). These earthquakes may be indicative of the Ottawa-Bonnechere graben faults reactivation (Kumarapeli 1987), which is repercussion for the northeasterly oriented compression.

Four of the events showed thrust fault motion but on a northeast striking plane (events 20130524, 20150707, 20150727 and 20150817). One event indicated thrust fault motion on almost north-south striking direction (20140207). The almost east-west orientation of one thrust fault is unusual for the region (20131020). These six mechanisms showed a northwest orientation of the P axes (west P direction for event 20140207), which deviates from the typical stress axes orientation in this region. These uncommon mechanisms may be explained by variations in magnitude and orientation of the local stress field.

These changes in stress field can be created by perturbation due to intrusions or other anomalies in the local structures (e.g. mylonite zone) in the northern part of the Ottawa River (Street et al., 1974; Wahlstrom, 1987) or caused by reactivation of older weak zones generated through early stress patterns (Sykes, 1978; Herget, 1980; Forsyth, 1981; Sanford et al., 1984 and 1985; and Gephart and Forsyth, 1985).

However, the thrust faulting patterns on moderately dipping planes for thirteen events were consistent with the regional seismicity pattern (Wahlstrom, 1987; Adams et al., 1988, 1989; Adams, 1991; Bent, 1996a, 1996b; Bent et al., 2003).

Four events had strike-slip faults and all of these had one northeast striking nodal plane (events 20130904, 20140704, 20150420 and 20150805) and their solutions represented northeast oriented P axes, which are consistent with the regional stress field.

Focal mechanisms for some events with close epicentral distances differed from each other (for example, events 20140704 and 20150817, 20150727 and 20130904, 20150808 and 20130116-A). Possible explanation for these variations may be various lineaments with different orientations (Kumarapeli, 1987) that express surficial features of the regional fracture pattern on Earth's surface.

6.2 FOCAL MECHANISM SOLUTION USING ONLY THE CNSN DATA

In order to determine whether the USTA stations are crucial to the focal mechanism solutions, the FOCMEC program was rerun using only the CNSC data (without the USTA) for those 30 events. Table 6.3 represents the strike, dip, rake, trend and plunge for seventeen events. The resulting nodal planes were compared with the results obtained using both CNSN and USTA data in Figure 6.3.

Table 6.3: Focal mechanism solutions obtained by using only the CNSN data

Date	Plane 1			Plane 2			P - axis		T - axis		B -axis	
	Strike °	Dip °	Rake °	Strike °	Dip °	Rake °	Trend °	Plunge °	Trend °	Plunge °	Trend °	Plunge °
20130116-A	18	21	44	246	76	106	323	29	176	57	62	15
20130116-B	130	5	90	310	85	90	40	40	220	50	130	0
20130517-A	124	54	59	351	46	126	236	5	336	65	144	25
20130517-B	147	54	59	13	46	126	258	5	358	65	166	25
20130517-C	312	60	84	144	30	100	46	15	207	74	315	5
20130524	16	22	63	224	70	101	306	25	151	63	41	10
20130904	323	16	-18	71	85	-105	325	48	174	39	72	15
20131020	107	40	61	323	56	112	37	9	283	76	130	18
20140207	168	52	71	17	42	113	271	5	19	74	180	15
20140704	350	15	-23	100	84	-104	354	49	202	38	101	14
20150404	331	10	37	205	84	98	288	39	124	50	24	8
20150420	281	71	36	178	56	157	47	10	145	38	305	50
20150707	345	19	18	236	84	108	311	37	165	48	55	18
20150715	134	40	82	315	54	68	74	11	138	65	301	33
20150727	211	53	62	72	45	122	320	5	61	67	228	22
20150805	undefined											
20150817	10	47	62	228	49	117	302	3	206	66	33	24

The resulting focal mechanism solutions obtained by using all available data (CNSN + USTA) and only the CNSN data are compared in Figure 6.3. There are some notable points, where the addition of the USTA data was truly worthwhile in attempting the focal mechanism solution and where it did not make much difference:

- Using only the CNSN data provided an undefined focal mechanism solution for event 20150805 whereas combined data set allowed for a well constrained focal mechanism solution.

- When only the CNSN data were used, two groups of possible solutions were obtained for event 20130517-C. However, with the adding of the USTA data, one group of solutions was removed, which shows the value of using the denser network.
- The number of solutions was reduced when the USTA data were added in events 20130524 and 20150715.
- There were not significant differences between the two solutions in events 20130517-A and 20150817.
- The orientation of nodal planes was considerably changed in events 20150420, which may have been due to the use of more first arrivals and take-off angles in the determination of the solutions.
- In some events, such as 20130517-B and 20150404, more solutions were obtained when the USTA data were added; however, the solutions had less variation, due to the use of a finer grid search in the program.
- The Ladysmith earthquake (20130517-A) has a previously published solution (Bent et al., 2015) that included data from some of the USTA stations. The solution obtained with the additional USTA data obtained in this study is in agreement with this previous solution.

Figure 6.3: Comparison between focal mechanism solutions obtained using all available data (CNSN + USTA) and only the CNSN data.

Based on the results shown in Figure 6.3, the preferred solutions in most events came from the combined data set, except in event 20150727, where the solution using only the CNSN data suggested a better constrained solution, and in events 20130517-A and 20150817, where the solutions were similar with both data sets.

The obtained results show that the addition of the USTA data resulted in relatively better constrained solutions although the solutions were generally similar in both cases. The strike, dip and rake parameters derived from the focal mechanism solutions using only the CNSN data were different for those obtained using both CNSN and USTA data.

The presented comparison in Figure 6.3 suggests that the orientation of some of the nodal planes has slightly changed when both CNSN and USTA data are used (for example, events 20130116-B and 20131020) and it has totally changed for event 20150420. For one event (20150805) well-constrained solution is obtained which was undetermined when only the CNSN data is used. Furthermore, accurate orientation of the undetermined nodal planes can be identified after adding the USTA data to the CNSN data.

According to the results shown in Figure 6.3, while better constrained solutions can be obtained for some of events with the addition of the USTA station data, the focal mechanism solutions were not considerably changed when the dense seismic network was used. Therefore, it can be concluded that the additional stations do not significantly affect the determination of focal mechanism solutions for earthquakes with magnitudes less than 4 and that the use of the current CNSN network on a routine basis is valuable in obtaining focal mechanisms for these events.

7. CONCLUSIONS

Seismograph station coverage in the Western Quebec Seismic Zone (WQSZ) was increased with the deployment of the US Transportable Array (USTA) from 2013 to 2015. This unparalleled data set allowed us improved monitoring of the seismic activity in the WQSZ. This study includes the results of the investigation into the ability of the additional USTA stations to increase our knowledge about epicentres and focal depths for three sets of events, including the aftershock sequence of the 2010 Val-des-Bois earthquake (Set #1) and the aftershock sequence of the 2013 Ladysmith earthquake (Set #2) and 18 earthquakes with magnitudes of ≥ 3.0 (Set #3) that occurred between January 2013 and July 2015. The focal mechanisms solutions were also determined for all events with magnitudes of ≥ 3.0 that occurred during 2013-2015, including events in Set #3 and twelve more.

The double-difference (DD) algorithm was used to relocate the aftershocks hypocentres of the events of Sets #1 and #2, which included 45 and 50 aftershocks, respectively. Due to the sensitivity of the location programs to the employed velocity model, the DD program was run using five different velocity models. Since a dense coverage of seismic stations is required to determine reliable hypocentre locations, all possible CNSN and USTA data were used to obtain locations. The joint hypocentre determination (JHD) method was also used to relocate hypocentres of the events in Sets #1 and #2, the results of which were compared with those of the DD technique.

The events in Set #3 were relocated using the standard travel times inversion method for two cases: 1) data from all seismic stations, and 2) data from the three closest stations.

The distribution of the relocated epicentres for both aftershock sequences (Sets #1 and #2) showed a northwest direction, and corresponded with the general seismicity trend of the

study region and was similar to previously published epicentres. Overall, the distribution of the relocated epicentres using both CNSN and USTA data demonstrated only slight changes in the seismicity trend, with movement toward the southwest for the Val-des-Bois aftershocks and toward the southeast for the Ladysmith aftershocks. These movements in both sets were more considerable in small events, due to the favourable coverage in station distribution when the combined CNSN and USTA data set was used.

Overall, there were small differences in the solutions obtained by the different velocity models. However, the relocated epicentres using velocity models 1, 2 and 5 were more tightly clustered, suggesting that these models may be the better choices for estimation of earthquake location by the DD technique in the region. The overall pattern of seismicity was more focused when both CNSN and USTA data sets were used, except the relocations in velocity model 2, which were remarkably different. This pattern can be defined as a linear feature striking on northwest-southeast direction similar to the regional seismicity pattern.

The comparison between distributions of the relocated epicentres using the JHD method and the DD technique through velocity model 5 showed the same general pattern of seismicity trend with slight movement toward the southwest associated with lower values of uncertainties when the JHD method was used for events in both Set #1 and Set #2. Generally, the epicentres are more tightly clustered in DD technique for both sets.

The distribution of the earthquake epicentres of Set #3 showed a northwest trend of seismic activity with both free and fixed depths. As expected (their locations had already been well determined in the Geological Survey of Canada (GSC) catalog), the comparison between

the results did not show any remarkable differences in epicentres when the data from the USTA was added to those from the CNSN.

The denser station coverage reduced the values of the epicentral location uncertainties, resulting in slightly better constrained locations.

The relocated focal depths showed a slight shift toward shallower depths when velocity models 1 and 2 were used for the aftershock sequence of the Val-des-Bois earthquake (Set #1) and when velocity models 1, 2 and 5 were used for the aftershock sequence of the Ladysmith earthquake (Set #2). The results had lower uncertainties when the combined data set was used. The relocated hypocentres revealed that events on the northeast side of Set #1 were relatively shallower than those on the southwest side, which can be interpreted as a plane with a west dipping direction.

The relocated focal depths of the aftershock sequence of the Ladysmith earthquake (Set #2) displayed an almost northwest-southeast seismicity trend. It seems that events on the southwest side were relatively shallower than those in other parts, which can be interpreted as a northeastern dipping plane with a northwest striking direction (a 130° striking plane with a 54° dip angle), similar to one of the fault planes obtained from the focal mechanism solution.

The comparison between distributions of the relocated focal depths determined using the JHD method and the DD technique through velocity model 5 showed slight changes in depth. When the JHD method was used, the relocated depths were closer to 18 km associated with lower values of uncertainties for Set #1, and were deeper associated with higher values of uncertainties for Set #2.

The dominant seismogenic layers where these aftershock sequences occurred are located at a depth of about 16.5 to 19.5 km for Set #1 and about 12 to 18 km for Set #2; these results are compatible with most parts of the WQSZ.

The focal depths of the events in Set #3 ranged from 9 to 21 km, corresponding to shallow to mid-crustal depths, which is typical of the WQSZ (Bent and Perry, 2002; Ma and Atkinson, 2006; Bent et al., 2015). More reliable focal depths could be obtained for these events, which have fixed depths in the GSC catalog, using the denser seismic network with the inclusion of the USTA data. The results showed that different combinations of stations in the DD technique and the different methods (JHD and DD) with the same velocity model gave very similar relocated depths.

Since records in close epicentral distances (Gomberg et al., 1990) is a strong constraint on the determination of focal depths, the favourable dense coverage, in terms of distance, provided by the additional USTA could be successful in obtaining more accurate hypocentres for small earthquakes.

Focal mechanism solutions using both CNSN and USTA data for seven of the thirty events were consistent with the regional pattern of thrust faulting on northwest striking planes, which is similar to larger earthquakes in the region and is in agreement with previous studies (Wahlstrom, 1987; Adams et al., 1988, 1989; Adams, 1991; Bent, 1996a, 1996b; Bent and Drysdale, 2000, 2001; Bent et al., 2003; Ma and Motazedian, 2012; Bent et al., 2015). Four events were indicative of a thrust fault on a northeast striking plane. The almost east-west and north-south orientation of two events were unusual for the region. The focal mechanism solutions were also indicative of four strike-slip faulting.

While well constrained strikes of the nodal planes for thirteen events could not be determined from the focal mechanism solutions, the orientation of their P axis (the maximum compression direction), T axis (the maximum tension direction) and B axis (the intermediate stress axis or intersection of the nodal planes) are relatively well defined for some of them. The majority of the solutions present a nearly northeast orientation for the P axes and a small plunge, which demonstrate a horizontal component for them that is in agreement with regional compressive stresses and previous studies (Adams and Basham, 1991; Zoback, 1992; Adams, 1995). Although better constrained focal mechanism solutions may be obtained for some events when a dense seismic network is used, extra stations are not needed to obtain focal mechanism solutions for earthquakes with magnitudes of less than 4.

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Data and Resources:

The Canadian National Seismograph Network (CNSN) - Earthquakes Canada, GSC, Earthquake Search (On-line Bulletin), <http://www.earthquakescanada.nrcan.gc.ca/stndon/NEDB-BNDS/bull-en.php>, {June 2016_accessed}.

Data from the TA network were made freely available on <http://ds.iris.edu/ds/nodes/dmc/forms/breqfast-request>.

Data retrieved from the ISC web site: International Seismological Centre (2013). On-line Bulletin, <http://www.isc.ac.uk>, Internatl. Seis. Cent., Thatcham, United Kingdom.

The maps in this study are generated using General Mapping Tools (GMT) (Wessel and Smith, 2015).

MATLAB and Statistics Toolbox Release 2012b, The MathWorks, Inc., Natick, Massachusetts, United States.

APPENDIX A— RELOCATED RESULTS FROM DOUBLE-DIFFERENCE ALGORITHM

Relocated Aftershocks in hypoDD for Val-des-Bois earthquake using both CNSN and USTA data, MAXSEP=5, NITER=2 (Velocity model 1*)

Table A.1: The relocated hypocentres of the Val-des-Bois earthquake aftershocks, using both CNSN and USTA data, calculated from the hypoDD program using MAXSEP = 5, NITER = 2 & velocity model 1 (V1). * means depth was fixed. X, Y, Z indicate east-west, north-south, depth location (m) relative to cluster centroid, respectively. EX, EY, EZ indicate east-west, north-south, depth error (m), respectively. A summary of the events identification can be found in Table 4.1.

ID	X	Y	Z	EX	EY	EZ	Depth	
							catalog	HypoDD
1	-1163	1638.6	-163.2	57.8	33.4	48.2	18.00*	17.81
5	470.9	-1928.5	1694.4	241.5	96.5	75.5	20.40	19.67
8	88.2	-582.9	647.8	81.9	36.2	90.6	18.00*	18.62
9	-407.9	-493.4	1024.3	1618.9	965.9	808.6	18.00*	19.00
1	-186.7	-551.8	471.5	86.1	53.3	105.8	18.00*	18.44
12	-2241.9	1811.1	-452.8	72.7	60.2	100.2	18.00*	17.52
13	1811.4	-1515	600.3	150.6	98	207.9	18.00*	18.57
16	-1605.4	336.7	-1998.8	128	115.9	1750.5	18.00*	15.97
20	2148	-1591.3	-880.1	146.4	85.4	218.1	18.00*	17.09
24	3154.4	-2143.1	-711.1	327.9	143.7	600	18.00*	17.26
25	2980	-1597	370	1406.8	633.1	1186.8	18.00*	18.34
28	-336.4	318.7	-573	67	60.7	88.9	18.00*	17.40
30	1891.8	-2157.6	-1442.2	175.8	94.9	283.8	18.00*	16.53
31	-1891.3	-126.3	747.8	217.9	67.9	258.8	18.00*	18.72
33	3328.6	918.7	1720.8	3583.3	1378.8	1922.8	18.00*	19.69
36	3284.5	3201.2	-148.1	303	311.5	172.2	18.00*	17.82
37	-2990.6	-889.6	-477.7	1866.3	579.4	1168.5	15.00	17.49
38	-4460.3	3177.7	38.3	591.2	702.4	828.4	18.00*	18.01
39	-4213.7	463	1392.9	1734.3	179.5	1630.4	18.00*	19.36
40	-3158	-736.6	-1726	804.8	612.4	1157.1	18.00*	16.25
41	3487.1	2454.5	-135.1	1039.3	299.8	428.7	18.00*	17.84

*Velocity model (1): Brune and Dorman (1963)

NLAY: 4 number of model layers

Table A.2: Velocity model (1) used in hypoDD program

TOP:	P-wave velocity:
Depth to the top of layer (km)	Layer velocity (km/s)
0.0	5.64
6.0	6.15
16.0	6.60
36.0	8.10

Figure A.1: projection of the relocated Val-des-Bois earthquake aftershocks, using MAXSEP 5 & velocity model 1 (V1)

Figure A.1 presents the projections of the relocated aftershocks of the Val-des-Bois earthquake (set #1). The distribution of stations which are used in the hypocentral determination, is displayed in the upper-left segment; The distribution of epicentres with error bars is shown in the upper-right segment; there are two cross-section shown as A-A' and B-B' in upper-right segment, the orientations of these cross-sections are chosen along and across the seismicity trend: The hypocentral projection on cross-section A-A' is illustrated in bottom-left segment and the projection on cross-section B-B' is displayed in bottom-right segment. This projection suggests a fault plane striking northwest-southeast, which is consistent with the result of the moment tensor and the closest double couple solution (shown on figure) obtained by Ma & Motazedian (2012) and with the pattern of earthquakes epicentres in the WQSZ in general (Bent, 1996a, b; Ma and Motazedian, 2012; Bent et al., 2015).

Relocated Aftershocks in hypoDD for Val-des-Bois earthquake using both CNSN and USTA data, MAXSEP=10, NITER=2 (Velocity model 1)

Table A.3: The relocated hypocentres of the Val-des-Bois earthquake aftershocks, using both CNSN and USTA data, calculated from the hypoDD program using MAXSEP = 10, NITER = 2 & velocity model 1 (V1). * means depth was fixed.

ID	X	Y	Z	EX	EY	EZ	Depth	
							catalog	HypoDD
1	-1879.2	715.9	42.4	42.2	30.5	42.3	18.00*	18.02
5	-27.2	-2848.9	1628.7	45.3	27.5	30.9	20.40	19.61
8	-72.1	-1256.2	387.7	35.4	19.7	34.7	18.00*	18.36
9	-807.8	-1346.2	656.7	81.8	49.7	58.2	18.00*	18.63
10	-386.1	9576	-201.5	121.1	100.6	64.1	18.00*	17.78
11	-244.4	-1388.7	-76.2	42	23.3	56.7	18.00*	17.90
12	-2496.8	978.6	-421.3	41.7	31	57.4	18.00*	17.56
13	1712.5	-2042.8	79.7	50.9	33.2	53.7	18.00*	18.06
16	-1946.8	-737.2	-2263.8	72.1	61.6	91.5	18.00*	15.71
20	1639.6	-2315.2	-754.6	97.6	61.6	168.3	18.00*	17.22
24	2838.4	-2620.8	-725.7	83	55.7	158.4	18.00*	17.25
25	3573.6	-1893.3	-777.9	72.5	46.8	114.4	18.00*	17.20
26	4743.1	3399.7	813.3	122.4	57.6	163.1	18.00*	18.79
27	5101.8	-3798.7	-1013.9	142.7	62.8	190.5	18.00*	16.96
28	-694.8	-508.1	-736.2	49.4	36.8	74.2	18.00*	17.24
30	1548.4	-2893.3	-1523.3	46.7	29	62.8	18.00*	16.45
31	-2073.4	-902.3	292.8	61.7	40.2	93.1	18.00*	18.27
33	3950.2	857.7	596.1	46.5	28.4	57.7	18.00*	18.57
36	3580.4	2301.4	43.9	106.2	50.5	137	18.00*	18.02
37	-8414.7	820.6	-4599.6	76.1	80.9	122.1	15.00	13.38
38	-5191.3	770.1	280.6	69	64.7	239.8	18.00*	18.26
39	-4667.1	-263.3	1110.1	44.6	38	56.7	18.00*	19.09
40	-6493.3	514.2	-2684.9	131.9	46.9	109.9	18.00*	15.29
41	3945.4	1444.1	-1019.4	256.4	338	180.8	18.00*	16.96
15	-2750.9	5766.8	43.6	0	0.1	0.1	18.00*	18.04
23	-2885.7	2181.7	144.8	0	0	0.1	18.00*	18.15
35	-466.5	4182.6	4420.1	0	0	0.1	18.00*	22.42
45	2379.2	-2997.6	-4283.1	0	0	0.1	18.00*	13.72

Figure A.2: projection of the relocated Val-des-Bois earthquake aftershocks, using MAXSEP 10 & velocity model 1 (V1)

Figure A.3: Comparison between hypocentral projections of Val-des-Bois aftershocks, obtained by MAXSEP 5 and 10 km

In Figure A.3 two sets of hypocentre locations for set #1, using MAXSEP 5 and 10 km in the hypoDD were compared to assess any differences. The average horizontal difference between MAXSEP 5 and 10 was 1.1 km. The comparison between MAXSEP 5 and 10 km indicates that

results obtained by MAXSEP 5 includes more focused clusters. By applying smaller value of maximum separation, the number of connected events will be decreased (Waldhauser, 2001). However, those earthquakes make strong links which cause improvement in event locations.

Figure A.4: The epicentral distribution of Val-des-Bois aftershocks using the velocity model 1 (V1)

Figure A.4 displays the distribution of epicentres obtained from the hypoDD using velocity model (1) and the GSC's catalog. The epicentres obtained by the GSC's catalog are displayed as the blue circles and the white stars show the relocated epicentres obtained by the hypoDD and the movement direction is shown by arrows. Comparison between these two dataset shows that the average, maximum and minimum distance between catalog and relocated epicentres are about 1.360, 4.374 (red arrow) and 60 metres, respectively.

Relocated Aftershocks in hypoDD for Val-des-Bois earthquake using both CNSN and USTA data, MAXSEP=5, NITER=2 (Velocity model 2*)

Table A.4: The relocated hypocentres of the Val-des-Bois earthquake aftershocks, using both CNSN and USTA data, calculated from the hypoDD program using MAXSEP = 5, NITER = 2 & velocity model 2 (V2). * means depth was fixed.

ID	X	Y	Z	EX	EY	EZ	Depth	
							catalog	HypoDD
1	-1201.8	1455.3	80.7	62.5	40.2	74.6	18.00*	18.05
5	344.5	-1957	1743.6	80.5	42.4	52.5	20.40	19.72
8	5.8	-649.3	728.6	65.7	29.1	80.7	18.00*	18.70
9	146.4	-688.8	1846.5	652.7	356.3	378.4	18.00*	19.82
11	-156.8	-696.5	395.6	65.2	36.4	112.7	18.00*	18.37
12	-2014.5	1696.6	-585.3	43.2	35.9	48.1	18.00*	17.39
13	1699.3	-1493.2	900.6	146	93.4	152.7	18.00*	18.87
16	-1615.5	115.8	-1034.6	110.3	60	222	18.00*	16.94
20	1767.4	-1659	-609	151.2	56.3	229.1	18.00*	17.36
24	2885.1	-2075	-303.3	127.9	64.6	297.5	18.00*	17.67
25	2728.9	-1475.2	142.3	2311.6	966.8	1567.8	18.00*	18.11
28	-618.8	61.6	-192.5	83.1	59.5	117.6	18.00*	17.78
30	1493.5	-2221	-980.8	59.3	43.2	142	18.00*	16.99
31	-1600.4	-206.3	471.7	198.9	55	304.8	18.00*	18.44
33	6913.9	4059.2	-1940.1	204220.9	68489	153851.5	18.00*	16.03
36	3618.6	2238.5	824.7	1561.1	2266.9	1071.7	18.00*	18.80
37	-2925.6	1027	-2901.5	118191.6	35774.5	43042	15.00	15.07
38	-4736.9	707.3	2612.7	29646.9	3648.4	118650.7	18.00*	20.58
40	-2311.6	891	-2262.8	115723.3	31838.9	42377.8	18.00*	15.71
41	2866.5	1652.5	-1404.5	4601.2	4584.7	5944.4	18.00*	16.57
15	1515	1431.7	-1811.2	0	0	0	18.00*	16.19
23	1086.1	-1699.9	-464.3	0	0	0	18.00*	17.54

**Velocity model (2):* Motazedian *et al.*, (2013)

NLAY: 10 number of model layers

Table A.5: Velocity model (2) used in hypoDD program

TOP:	P-wave velocity:
Depth to the top of layer (km)	Layer velocity (km/s)
2.0	6.20
6.0	6.16
10.0	6.11
14.0	6.18
17.0	6.27
21.0	6.46
24.0	6.41
28.0	6.33
33.0	6.33
40.0	6.83

Figure A.5: projection of the relocated Val-des-Bois earthquake aftershocks, using MAXSEP 5 & velocity model 2 (V2)

In Figure A.5, some events (33, 36, 37, 38, 40 and 41) show high uncertainties. This might be related to the velocity structure which determines the ray paths and take-off angles and cause travel time derivatives.

Relocated Aftershocks in hypoDD for Val-des-Bois earthquake using both CNSN and USTA data, MAXSEP=10, NITER=2 (Velocity model 2)

Table A.6: The relocated hypocentres of the Val-des-Bois earthquake aftershocks, using both CNSN and USTA data, calculated from the hypoDD program using MAXSEP = 10, NITER = 2 & velocity model 2 (V2). * means depth was fixed.

ID	X	Y	Z	EX	EY	EZ	Depth	
							catalog	HypoDD
1	-1660.2	763.2	74.2	42	22.1	38.2	18.00*	18.05
5	342	-2581.9	1616.1	34.9	19.9	31.2	20.40	19.59
8	-48	-1394.4	267.9	27.9	16.3	29.1	18.00*	18.24
9	-21.1	-1122.9	1485.8	60.6	38.6	36.2	18.00*	19.46
10	-381	9218.5	-150.7	77.7	80.5	59.9	18.00*	17.83
11	-532.8	-1308.5	355.9	28	24	39.2	18.00*	18.33
12	-2418	1020.4	-538.3	28.8	20.2	32.2	18.00*	17.44
13	1535.4	-2028.1	279.2	33.8	22.6	47.8	18.00*	18.26
16	-2164.1	-681.4	-1851.1	45.4	42	95.3	18.00*	16.13
20	1496.5	-2264.1	-912.4	80.4	48.9	168.4	18.00*	17.06
24	2734.3	-2460.9	-568.3	52.1	44.5	102.7	18.00*	17.41
25	3206.5	-1836.9	-246	44.8	29	108.9	18.00*	17.73
2	4711.8	3089.3	629.8	116.1	54.8	121.3	18.00*	18.61
27	4349.1	-3884.6	-910.9	89.6	56.4	155.1	18.00*	17.07
28	-884.1	-557.6	-390.2	65	35.6	80.5	18.00*	17.59
30	1246.4	-2783.3	-1351.2	41.3	29.2	62.4	18.00*	16.63
31	-2214.9	-971.3	646.6	51.8	36.9	74.4	18.00*	18.62
33	3691.7	822.4	904.9	36	22.2	51.5	18.00*	18.88
36	3661.7	1546.2	1384.7	53	29.6	67.8	18.00*	19.36
37	-8050	504.6	-5059.7	71.2	44.6	101.7	15.00	12.92
38	-4913.5	1275.3	214.9	55.2	103.7	131.2	18.00*	18.19
39	-4942	-512.4	1817.8	33.5	32.8	79.3	18.00*	19.79
40	-7006.6	561.8	-3504.8	104.4	26.3	143.1	18.00*	14.47
41	3721.6	1742.1	-1557.1	94	111.3	144.8	18.00*	16.42
15	-5823.7	4720	3279.4	0	0.3	0.1	18.00*	21.28
19	13368.4	-7300.5	-6848.9	0.1	0.1	0.2	18.00*	11.15
23	-6473.6	1353.1	4959.5	0	0.3	0.2	18.00*	22.96
35	-12031.7	4688.5	2991.2	0.1	0.1	0.1	18.00*	20.99
45	10968.9	-3690.7	-4470.6	0.2	0.7	0	18.00*	13.53

Figure A.6: projection of the relocated Val-des-Bois earthquake aftershocks, using MAXSEP 10 & velocity model 2 (V2)

Comment:

Compare the results from these two different velocity models shows nearly 1 km changes in depth and errors. (Mostly increase in errors). Increasing the number of layers doesn't effect on the trend of the epicentral locations. The average epicentre difference was 1.0 km and the average difference in focal depths was 0.8 km.

Figure A.7: The epicentral distribution of Val-des-Bois earthquake aftershocks using the velocity model 2 (V2)

The distribution of epicentres obtained from the hypoDD using velocity model (2) and the GSC's catalog is represented in Figure A.7. The epicentres obtained by the GSC's catalog are displayed as the blue circles and the green-yellow diamonds show the relocated epicentres obtained by the hypoDD program (velocity model 2) and the movement direction for some of the relocated events is shown by arrows. Comparison between these two datasets shows that the average distance between catalog and relocated epicentres is 1.195 km, the maximum distance about 3.716 km (red arrow) and the minimum distance about 120 metres. This figure shows the overall trend is more focused when combined data set is used.

Relocated Aftershocks in hypoDD for Val-des-Bois earthquake using both CNSN and USTA data, MAXSEP=5, NITER=2 (Velocity model 3*)

Table A.7: The relocated hypocentres of the Val-des-Bois earthquake aftershocks, using both CNSN and USTA data, calculated from the hypoDD program using MAXSEP = 5, NITER = 2 & velocity model 3 (V3). * means depth was fixed.

ID	X	Y	Z	EX	EY	EZ	Depth	
							catalog	HypoDD
1	-1272.2	1241.5	-34.4	89.1	22.1	32.4	18.00*	17.94
5	157.6	-1839.3	1490.5	45	10.5	14.8	20.40	19.46
8	196.4	-234.5	635.3	33.1	30	20.3	18.00*	18.61
9	978.7	-23.3	1961	36	44.5	60.3	18.00*	19.93
11	-279.4	-331.4	550.7	18	17.1	54.6	18.00*	18.52
13	1690.5	-1697	1136.6	84.4	29.3	18.6	18.00*	19.11
20	1977.7	-1249.7	-1079.7	65	35.6	25.5	18.00*	16.89
24	3130.5	-1677	-1477.2	45	55.5	74.1	18.00*	16.49
25	3111.1	-969	-862.9	18.2	22.3	11.4	18.00*	17.11
28	-322.5	194.8	-551.5	36.6	28	31.1	18.00*	17.42
30	2235.5	-1667.2	-1929.5	22	17	15.6	18.00*	16.04
31	-2189.8	-120.7	1101.1	74.1	84.3	9	18.00*	19.07
36	2019.9	1385.1	475.5	10.4	9.8	1	18.00*	18.45
38	-4386.4	2411.1	1071.5	38.6	11.3	0.1	18.00*	19.04
39	-6626.9	-304.1	700	23.3	3.9	0	18.00*	18.67
15	208.8	1016.9	-1088.3	0.4	0	0.2	18.00*	16.91
23	817.9	-2687.1	-852.3	0	0.3	0.1	18.00*	17.15

*Velocity model (3): Motazedian and Ma (2014)

NLAY: 10 number of model layers

Table A.8: Velocity model (3) used in hypoDD program

TOP:	P-wave velocity:
Depth to the top of layer (km)	Layer velocity (km/s)
2.0	5.54
6.0	5.61
10.0	5.99
14.0	6.20
17.0	6.51
21.0	6.67
24.0	6.70
28.0	6.50
34.0	6.58
40.0	7.19

Figure A.8: projection of the relocated Val-des-Bois earthquake aftershocks, using MAXSEP 5 & velocity model 3 (V3)

Figure A.9: The epicentral distribution of Val-des-Bois earthquake aftershocks using the velocity model 3 (V3)

The distribution of epicentres obtained from the hypoDD using velocity model (3) and the GSC's catalog is represented in Figure A.9. The epicentres obtained by the GSC's catalog are displayed as the blue circles and the plus symbols show the relocated epicentres obtained by the hypoDD program (velocity model 3) and the movement direction is shown by arrows. Comparison between these two dataset shows that the average distance between catalog and relocated epicentres is 1.188 km, the maximum distance about 4.567 km (red arrow) and the minimum distance about 281 metres. This figure shows the overall trend is more focused when combined data set is used.

Relocated Aftershocks in hypoDD for Val-des-Bois earthquake using both CNSN and USTA data, MAXSEP=5, NITER=2 (Velocity model 4*)

Table A.9: The relocated hypocentres of the Val-des-Bois earthquake aftershocks, using both CNSN and USTA data, calculated from the hypoDD program using MAXSEP = 5, NITER = 2 & velocity model 4 (V4). * means depth was fixed.

ID	X	Y	Z	EX	EY	EZ	Depth	
							catalog	HypoDD
1	-1415	1372.7	-258.7	221.7	135.6	304.5	18.00*	17.71
5	631.7	-2194.8	1120.4	1005.5	225.5	845.5	20.40	19.09
8	-1041.7	-1042.9	960.7	874	742.2	800.5	18.00*	18.93
9	-277.2	-1080.1	1906.6	1546.6	1807.7	1663.2	18.00*	19.88
11	-930.1	-853.9	596.1	589.4	447.8	605.2	18.00*	18.57
12	-2574.9	1720.8	-1216.8	874.4	1088.7	1125.4	18.00*	16.76
13	1187.6	-1552.2	276.4	200.3	148.9	105.8	18.00*	18.25
16	-1829.7	-220.3	-1567.3	1087.8	1326.6	1405.9	18.00*	16.40
20	942.7	-2043.3	-222	366.5	587.8	100.5	18.00*	17.75
24	2455.2	-2469.1	-544.1	489.9	1135.2	401.5	18.00*	17.43
25	5064.6	-532.9	-1660.2	1025.5	1899.4	908.8	18.00*	16.31
28	-889.9	-46	-393.3	100.4	55.6	113.5	18.00*	17.58
30	427	-2851.4	-732.9	559.9	1400.1	303.3	18.00*	17.24
31	-3060.4	-533.1	1356.4	1035.5	1095.5	845	18.00*	19.33
36	946	485.3	456.3	333.6	322.3	122.3	18.00*	18.43
37	538.3	2405.1	-759.5	503	704.4	84.6	15.00	17.21
39	-5459.1	-60	1099	847.7	41.1	74	18.00*	19.07
40	1167.2	2548	-787	666.9	25.9	108.6	18.00*	17.18
41	4740.9	2335.9	-327.9	122.3	105.5	45	18.00*	17.64

*Velocity model (4): Darbyshire *et al.*, (2007)

NLAY: 4 number of model layers

Table A.10: Velocity model (4) used in hypoDD program

TOP: Depth to the top of layer (km)	P-wave velocity: Layer velocity (km/s)
0.0	6.41
15.0	6.41
35.0	6.93
45.0	7.79

Figure A.10: projection of the relocated Val-des-Bois earthquake aftershocks, using MAXSEP 5 & velocity model 4 (V4)

Figure A.11: The epicentral distribution of Val-des-Bois earthquake aftershocks using the velocity model 4 (V4)

The distribution of epicentres obtained from the hypoDD using velocity model (4) and the GSC's catalog is represented in Figure A.11. The epicentres obtained by the GSC's catalog are displayed as the blue circles and the pink triangles show the relocated epicentres obtained by the hypoDD program (velocity model 4) and the movement direction is shown by arrows. Comparison between these two dataset shows that the average distance between catalog and relocated epicentres is 2.115 km, the maximum distance about 7.176 km (red arrow) and the minimum distance about 371 metres.

Relocated Aftershocks in hypoDD for Val-des-Bois earthquake using both CNSN and USTA data, MAXSEP=5, NITER=2 (Velocity model 5*)

Table A.11: The relocated hypocentres of the Val-des-Bois earthquake aftershocks, using both CNSN and USTA data, calculated from the hypoDD program using MAXSEP = 5, NITER = 2 & velocity model 5 (V5). * means depth was fixed.

ID	X	Y	Z	EX	EY	EZ	Depth	
							catalog	HypoDD
1	154.6	1516.8	-184.9	103.3	56.6	42.3	18.00*	17.79
5	1481.6	-2353	1404	55	78.9	60.2	20.40	19.38
8	103.5	-1075.1	1192.2	48.9	20.5	60.7	18.00*	19.16
9	-386.7	-575.1	493.3	323.3	111	80.3	18.00*	18.47
11	205.7	-880.3	859.2	401.2	321.1	205.4	18.00*	18.83
12	-1093.6	2454.7	-1238.8	844.6	74.1	62.5	18.00*	16.73
13	2288.1	-1581.3	410	100	117.2	44.7	18.00*	18.38
16	-1299.4	203.6	774.4	189.9	235	68.9	18.00*	18.75
20	2107.2	-2055.3	-177.8	47.5	55.8	90.5	18.00*	17.79
24	3610.2	-2538.1	-1182.2	845.6	248.8	178.8	18.00*	16.79
28	623.3	85.9	-353.4	134.4	41	74.5	18.00*	17.62
30	1576.9	-2842.7	-565.9	87.9	404.1	22.3	18.00*	17.41
31	-2134	-582.4	2078.4	47.5	331.3	20.8	18.00*	20.05
36	3768.2	2268.9	-195.1	147.7	210.5	87.7	17.78	17.78
37	-3460.1	3533.7	210.4	225.5	30.8	44.7	18.00*	18.18
38	-2630.1	963.3	1794.7	87.9	200	21.1	18.00*	19.77
15	518.3	1241.1	-725.4	25.6	54	12.4	18.00*	17.28
23	-54.1	-2176	-1166.4	33.2	32	10.5	18.00*	16.83
35	-464.2	934.9	1891.8	21.1	33	24.5	18.00*	19.89

**Velocity model (5)*: obtained from VELEST program (see section 3.2.3.1 in chapter 3)

NLAY: 5 number of model layers

Table A.12: Velocity model (5) used in hypoDD program

TOP:	P-wave velocity:
Depth to the top of layer (km)	Layer velocity (km/s)
5.64	-1
5.92	0
6.46	6
6.46	16
8.21	36

Figure A.12: projection of the relocated Val-des-Bois earthquake aftershocks, using MAXSEP 5 & velocity model 5 (V5)

Figure A.13: The epicentral distribution of the Val-des-Bois earthquake aftershocks using the velocity model 5 (V5)

The distribution of epicentres obtained from the hypoDD using velocity model (5) and the GSC's catalog are represented in Figure A.13. The epicentres obtained by the GSC's catalog are displayed as the blue circles and the relocated epicentres obtained by the hypoDD program (velocity model 5) are shown by light brown squares and the movement direction is shown by arrows. Comparison between these two dataset shows that the average distance between catalog and relocated epicentres is 1.281 km, the maximum distance and the minimum distances are about 3.7 and 0.4 km. This figure shows the overall trend is more focused when combined data set is used.

Relocated Aftershocks in hypoDD for Val-des-Bois earthquake using both CNSN and USTA data, MAXSEP=2, NITER=3 (Velocity model 1)

Table A.13: The relocated hypocentres of the Val-des-Bois earthquake aftershocks, using both CNSN and USTA data, calculated from the hypoDD program using MAXSEP = 2, NITER = 3 & velocity model 1 (V1). * means depth was fixed.

ID	X	Y	Z	EX	EY	EZ	Depth	
							catalog	HypoDD
1	-2083.8	1753.8	1065.1	0	0	0	18.00*	19.07
8	-441.1	-150	534.7	0	0	0	18.00*	18.54
12	-3526.2	1550.4	965.5	0	0	0	18.00*	18.97
28	-1087	451	354.5	0	0	0	18.00*	18.35

Figure A.14: projection of the relocated Val-des-Bois earthquake aftershocks, using MAXSEP 2 & NITER 3

Relocated Aftershocks in hypoDD for Val-des-Bois earthquake using both CNSN and USTA data, MAXSEP=5, NITER=3 (Velocity model 1)

Table A.14: The relocated hypocentres of the Val-des-Bois earthquake aftershocks, using both CNSN and USTA data, calculated from the hypoDD program using MAXSEP = 5, NITER = 3 & velocity model 1 (V1). * means depth was fixed.

ID	X	Y	Z	EX	EY	EZ	Depth	
							catalog	HypoDD
1	-1495.5	1700.5	-265	61.7	38.4	89.1	18.00*	17.71
5	-637.9	-2362.1	2249.7	195.9	93.8	238.4	20.40	20.22
8	34.5	-790.3	798.6	104.7	108.4	99.1	18.00*	18.77
11	18.2	-317.8	750.1	97.9	101.8	166.7	18.00*	18.72
12	-3246.4	1602.1	742.6	255.2	80.1	350.5	18.00*	18.71
13	1141.9	-1666.7	365.1	152.3	101.2	88.6	18.00*	18.34
20	2650	-1363.7	-922.5	401.2	42.6	148	18.00*	17.05
24	2524.5	-1792.6	-228.1	83.9	141.8	567.1	18.00*	17.74
25	4161.9	-615.7	-2003.1	455.8	140	1074.9	18.00*	15.97
28	251.1	166.5	-281.2	508.8	131.9	484.5	18.00*	17.69
30	849.6	-2140.2	-176	290.4	112.4	731.9	18.00*	17.80
31	-2019.8	-111	675.7	74.4	87.9	19.3	18.00*	18.65
37	-2833.5	-1272.8	-1258.5	162.1	108	117.6	15.00	16.71
40	-2206.2	-917.9	-2040.2	96.5	21.9	128.3	18.00*	15.93

Figure A.15: projection of the relocated Val-des-Bois earthquake aftershocks, using MAXSEP 5 & NITER 3

Relocated Aftershocks in hypoDD for Val-des-Bois earthquake using both CNSN and USTA data, MAXSEP=10, NITER=3 (Velocity model 1)

Table A.15: The relocated hypocentres of the Val-des-Bois earthquake aftershocks, using both CNSN and USTA data, calculated from the hypoDD program using MAXSEP = 10, NITER = 3 & velocity model 1 (V1).
* means depth was fixed.

ID	X	Y	Z	EX	EY	EZ	Depth	
							catalog	HypoDD
1	-1922.5	709.1	131.7	20.5	17.6	27.2	18.00*	18.11
5	-13.1	-2853.1	1606.4	41.6	31.9	38.6	20.40	19.58
8	-67.1	-1280.2	397.6	41.1	24.7	37.2	18.00*	18.37
9	-748.9	-1360.8	632.7	89.1	66.2	54.2	18.00*	18.61
10	-370.6	9771.5	-90.3	113.1	79.6	69	18.00*	17.89
11	-378.5	-1393.6	51.8	36	18.6	48.1	18.00*	18.03
12	-2523.6	1006.1	-507.8	16.3	25.7	27.8	18.00*	17.47
13	1667.5	-2051.6	74.2	39.8	25.6	38.5	18.00*	18.05
16	-1744.2	-652.1	-2229.8	163	143	136.2	18.00*	15.75
20	1438.4	-2405.9	-629.5	91	57.4	128.2	18.00*	17.35
24	2968.8	-2502.3	-995.1	85	53.3	134.3	18.00*	16.98
25	3571.2	-1927.3	-712.8	77.1	56.5	99.9	18.00*	17.26
26	4729.2	3419.5	959.6	107.6	53	138	18.00*	18.94
27	5066.4	-3795.3	-953.3	273	113	254.9	18.00*	17.02
28	-763.5	-502.1	-696.1	59.4	33.3	57.4	18.00*	17.28
30	1554.8	-2895.8	-1550.3	26.6	17.1	37.9	18.00*	16.43
31	-1964	-894.8	202	57.4	32.2	69.1	18.00*	18.18
33	3846.2	854.4	768.6	34.6	20.5	51.2	18.00*	18.75
3	3559.1	2305.2	-73.6	60.2	36.7	94	18.00*	17.90
37	-8336.3	861	-4648.5	77.1	74.3	126	15.00	13.33
38	-5081.1	780.3	199.2	93.4	59.3	266.8	18.00*	18.18
39	-4624.6	-241	1107	52.9	27.3	43.2	18.00*	19.08
40	-6529.7	555.6	-2802.8	145.2	43.3	85.1	18.00*	15.17
41	3904.5	1057.7	-1107.4	142.1	277.7	136.4	18.00*	16.87

Figure A.16: projection of the relocated Val-des-Bois earthquake aftershocks, using MAXSEP 10 & NITER 3

Relocated Aftershocks in hypoDD for Val-des-Bois earthquake using both CNSN and USTA data, MAXSEP=5, NITER=5 (Velocity model 1)

Table A.16: The relocated hypocentres of the Val-des-Bois earthquake aftershocks, using both CNSN and USTA data, calculated from the hypoDD program using MAXSEP = 5, NITER = 5 & velocity model 1 (V1). * means depth was fixed.

ID	X	Y	Z	EX	EY	EZ	Depth	
							catalog	HypoDD
5	340.1	-2094.1	1428.2	0	0.5	0.4	20.40	19.40
8	88.8	-502.1	1137.3	0.4	0.1	0.4	18.00*	19.11
11	-433.7	-251.8	164.3	0.2	0.1	0.3	18.00*	18.14
12	-2217.3	1313.3	-581.9	0.4	0.4	0.4	18.00*	17.39
13	1291.7	-1715.4	1343.2	2	0.3	2.2	18.00*	19.32
20	1859	-1490.4	-864.8	0.2	0.1	0.1	18.00*	17.11
24	2678.6	-1595.5	-609.8	0.2	0.1	0.2	18.00*	17.36
25	2954.6	-1593.8	-2663.3	0.2	0.1	0.2	18.00*	15.31
28	-935.6	23	-811.9	0.2	0.1	0.2	18.00*	17.16
30	451.6	-3143.4	1946.8	0.2	0.1	0.2	18.00*	19.92
31	-1896.8	-62.2	531.5	0.2	0.1	0.2	18.00*	18.50
15	647.8	1347.7	69.3	0	0	0	18.00*	18.07
23	894.7	-1848.7	-503.3	0	0	0	18.00*	17.50

Figure A.17: projection of the relocated Val-des-Bois earthquake aftershocks, using MAXSEP 5 & NITER 5

Relocated Aftershocks in hypoDD for Val-des-Bois earthquake using both CNSN and USTA data, MAXSEP=10, NITER=5 (Velocity model 1)

Table A.17: The relocated hypocentres of the Val-des-Bois earthquake aftershocks, using both CNSN and USTA data, calculated from the hypoDD program using MAXSEP = 10, NITER = 5 & velocity model 1 (V1). * means depth was fixed.

ID	X	Y	Z	EX	EY	EZ	Depth	
							catalog	HypoDD
1	-1930.7	637.8	122.1	0	5	4	18.00*	18.10
5	222.6	-2684.9	1651.3	6.1	5.4	4.6	20.40	19.63
8	-148.7	-1356.9	207.3	2	1.9	3	18.00*	18.18
10	192.9	9798.9	-212.7	3.8	10.6	6	18.00*	17.76
11	-178.2	-1386.6	70.5	7.6	3.4	7.8	18.00*	18.05
12	-2507.9	994.3	-421	3.7	0.5	3.2	18.00*	17.56
20	2023.5	-2374	-1648.7	2.3	3.8	3.2	18.00*	16.33
24	3043.7	-2585.1	-1163.5	2.2	3.3	4.8	18.00*	16.81
25	3631.8	-2018.7	-893.3	1.5	0.9	0.7	18.00*	17.08
26	5109.8	3863.1	505.3	1.5	2	2.2	18.00*	18.48
27	4610.9	-3866	-370.5	2.8	3.2	1.8	18.00*	17.61
28	-934.8	-468.1	-772.6	3.4	3.5	6.2	18.00*	17.20
30	1645.9	-2879.7	-1630.9	7.8	11.4	5.5	18.00*	16.35
31	-2038.7	-876	692.8	2.2	2.8	0.9	18.00*	18.67
33	3680	779.6	750.6	1.4	2.5	0.9	18.00*	18.73
36	3564.4	2639.8	-258.9	1.8	3.3	2.6	18.00*	17.72
38	-5330.3	881	438.8	2.3	4.2	1.2	18.00*	18.42
39	-4807.9	-291.8	1124.9	1.4	1.9	1.1	18.00*	19.10

Figure A.18: projection of the relocated Val-des-Bois earthquake aftershocks, using MAXSEP 10 & NITER 5

Relocated Aftershocks in hypoDD for Ladysmith earthquake using both CNSN and USTA data, MAXSEP=5, NITER=2 (Velocity model 1)

Table A.18: The relocated hypocentres of the Ladysmith earthquake aftershocks, using both CNSN and USTA data, calculated from the hypoDD program using MAXSEP = 5, NITER = 2 & velocity model 1 (V1). * means depth was fixed. X, Y, Z indicate east-west, north-south, depth location (m) relative to cluster centroid, respectively. EX, EY, EZ indicate east-west, north-south, depth error (m), respectively. A summary of the events identification can be found in Table 4.3.

ID	X	Y	Z	EX	EY	EZ	Depth	
							catalog	HypoDD
1	652.3	-784.3	305	10.9	23.8	26.9	13.50	14.07
2	291.4	-149.3	-101.6	8.3	16.2	16.9	14.00	13.67
4	-773.6	2863.3	987.3	15.8	42.5	23.1	14.53	14.76
5	845.4	-1385	-1028	15.3	41.2	30.8	12.00	12.74
6	586.7	25.4	-561.2	11.5	40.8	45.1	14.48	13.21
7	-349.8	-1039.7	-2388.6	32.3	108	149.6	9.91	11.38
8	-676	1560.6	872.2	20.6	63.8	34.8	14.43	14.64
9	-1361.2	-527.1	-992.6	16.2	40.7	38.9	11.45	12.78
10	25.1	90.6	117.1	10	20.2	16.9	13.96	13.89
11	66.7	-1053.8	-1335.6	22.1	42.7	49.6	12.00*	12.43
19	-1119.3	1667.4	-696.2	38	40	32.3	12.00*	13.07
21	1560.2	1114	-1091.5	33.6	111.1	94.6	12.00*	12.68
26	-730.5	-403.5	-2465.7	41.4	325.1	407.9	12.00*	11.30
27	484.1	-323.9	86.1	16.4	39.9	35	14.56	13.86
32	-75.3	-1140.2	-1037	20.4	50.9	65	12.00*	12.73
33	-208.7	-101.5	-145.5	11.5	21.9	22.8	13.50	13.62
35	292.4	-49.8	-294.7	18.6	47.2	48	12.98	13.47
38	-226.4	-211.6	-284.3	11.2	31	31.7	13.33	13.48
39	-291.9	-463.7	-534.6	21.5	34.2	40.4	13.19	13.23
40	-249.4	-877.1	-2221.3	65.8	63.4	102	13.97	11.55
42	101.1	-120.7	-110.4	20.4	37.7	35.8	13.46	13.66
43	-749.8	-1223	-1643.2	20.9	40	53.5	12.00*	12.13
44	874.8	1283.8	3245.8	32.2	106.5	72.3	18.00	17.01
45	321.8	133.6	3946.2	23.3	40.9	58	18.00	17.72
46	-360.6	1224.3	3001.6	28.7	107.6	48.4	18.00	16.77
47	439.5	-1570.9	4214.1	34.3	80.8	412.4	18.00	17.98
50	620.8	1453.7	155.7	34.6	49.2	94.7	14.50	13.92

Figure A.19: projection of the relocated Ladysmith earthquake aftershocks, using MAXSEP 5 & velocity model 1 (V1), focal mechanism solutions are also shown.

Based on this projection (Figure A.19), the cluster trend is generally NW-SE, which is similar to the northwest direction obtained of the focal mechanism solution in this study.

Relocated Aftershocks in hypoDD for Ladysmith earthquake using both CNSN and USTA data, MAXSEP=2, NITER=2 (Velocity model 1)

Table A.19: The relocated hypocentres of the Ladysmith earthquake aftershocks, using both CNSN and USTA data, calculated from the hypoDD program using MAXSEP = 2, NITER = 2 & velocity model 1 (V1). * means depth was fixed.

ID	X	Y	Z	EX	EY	EZ	Depth	
							catalog	HypoDD
1	812.8	-796.3	679.9	12.6	26.4	27.6	13.50	13.91
2	487.7	-116.2	447.4	9.7	19.8	24.8	14.00	13.68
4	-625.2	893.6	1668.8	219.5	558	250.5	14.53	14.90
6	766.3	40.9	62.1	19.1	58.7	71.4	14.48	13.29
8	-436.5	1876	1605.3	218.2	588.9	274.6	14.43	14.84
9	-1162.4	-1279.7	-1424.3	63.3	152.6	185.9	11.45	11.81
10	289.6	269.5	711.9	12.8	28.8	21.2	13.96	13.94
11	110.5	-1213.2	-618	30.6	46.9	67	12.00*	12.61
27	566.7	-484.1	532.9	31.5	76.7	68.1	14.56	13.76
32	99.5	-1654.1	-1129.9	21.3	61	44.5	12.00*	12.10
33	26.9	89.9	520	19.7	41.5	41.3	13.50	13.75
35	661	-35.9	119.4	16.8	39	39.3	12.98	13.35
38	-10.9	-49.8	330.8	17	44.1	41.6	13.33	13.56
39	-239.1	-467.4	-121.2	14.3	29.4	28.3	13.19	13.11
42	300.8	-131.3	453	17.9	37.6	39.3	13.46	13.68
43	-712.5	-1417.2	-1421.4	18.5	39.2	50.1	12.00*	11.81

Figure A.20: projection of the relocated Ladysmith earthquake aftershocks, (MAXSEP 2 & velocity model 1)

Figure A.21: Comparison between projections of Ladysmith earthquake aftershocks, obtained by MAXSEP 5 and 2 km

The two sets of hypocentre locations for Ladysmith, using MAXSEP 2 & 5 km, were compared to assess any differences. The average horizontal difference was 0.15 km and the average difference in focal depth was 0.3 km.

Figure A.22: The epicentral distribution of Ladysmith earthquake aftershocks using the velocity model 1 (V1)

Figure A.22 displays the distribution of epicentres obtained from the hypoDD using velocity model (1) and the GSC's catalog. The epicentres obtained by the GSC's catalog are displayed as the blue circles and the white stars show the relocated epicentres obtained by the hypoDD program and the movement direction is shown by arrows. Comparison between these two dataset shows that the average distance between catalog and relocated epicentres is 0.532 km, the maximum distance about 1.392 km (red arrow) and the minimum distance about 11 metres. The trend does not show any change in direction.

Relocated Aftershocks in hypoDD for Ladysmith earthquake using both CNSN and USTA data, MAXSEP=5, NITER=2 (Velocity model 2)

Table A.20: The relocated hypocentres of the Ladysmith earthquake aftershocks, using both CNSN and USTA data, calculated from the hypoDD program using MAXSEP = 5, NITER = 2 & velocity model 2 (V2). * means depth was fixed.

ID	X	Y	Z	EX	EY	EZ	Depth	
							catalog	HypoDD
1	568	-891.8	459.3	8.3	16	32.4	13.50	14.23
2	259.8	-155.7	18.5	6.4	12.5	23.9	14.00	13.79
4	-1025.4	2863.7	1703.2	14.6	28.4	32.1	14.53	15.47
5	917.6	-1660.2	-1521.1	13.1	43.6	56.7	12.00	12.25
6	508.6	54.7	-634.7	10.2	30	67.9	14.48	13.13
7	-284.2	-2575.7	-4057.3	36.3	85.4	275.1	9.91	9.71
8	-683.4	1833.1	1751.3	15.3	37.5	41.7	14.43	15.52
9	-1327.4	-933.3	-1641.1	16.6	39.8	59.4	11.45	12.13
10	43.5	195.8	358.7	10.1	19.9	31.8	13.96	14.13
11	-2.4	-938.2	-1374.2	18.7	36.1	63.2	12.00*	12.39
19	-228.6	844.8	-0.5	41.8	41.2	47.9	12.00*	13.77
21	1541.7	453.9	-1112	24.8	44.9	80.7	12.00*	12.66
26	-688	-80.6	-989.8	42.7	90.7	174.8	12.00*	12.78
27	418.4	-363.2	189.7	11.5	24.7	44.6	14.56	13.96
32	1.1	-1056.1	-921.9	15.2	32.4	67.3	12.00*	12.85
33	-240	-86.2	-84	11.6	21.4	37.5	13.50	13.69
35	251.4	110.9	182.9	13	29.2	53.4	12.98	13.95
38	-195.9	-141	-212.1	11	23.7	47.1	13.33	13.56
39	-364.8	-517.5	-722.2	11.9	24.1	56.1	13.19	13.05
40	678.4	-185.5	-360.4	60.3	114.9	270.7	13.97	13.41
42	116.5	-270.9	-40.8	12.1	24.9	47.2	13.46	13.73
43	-807.3	-679.6	-1195.4	18.3	30.7	79.4	12.00*	12.57
44	660.2	1403.4	3567	52.8	88.5	104.7	18.00	17.34
45	-143	161.6	2263.9	14.4	28.7	70.2	18.00	16.03
46	-626.4	2088.4	4031.8	26.6	45.8	49.3	18.00	17.80
47	472.9	-1237.4	5738.2	25	46.8	162.8	18.00	19.51
50	165.7	1755.8	-5394.9	29.7	59.4	476.9	14.50	8.37

Figure A.23: projection of the relocated Ladysmith earthquake aftershocks, using MAXSEP 5 & velocity model 2 (V2)

Relocated Aftershocks in hypoDD for Ladysmith earthquake using both CNSN and USTA data, MAXSEP=2, NITER=2 (Velocity model 2)

Table A.21: The relocated hypocentres of the Ladysmith aftershocks, using both CNSN and USTA data, calculated from the hypoDD program using MAXSEP = 2, NITER = 2 & velocity model 2 (V2).
* means depth was fixed.

ID	X	Y	Z	EX	EY	EZ	Depth	
							catalog	HypoDD
1	478.3	-752.6	366.5	13.8	34.4	113.8	13.50	13.60
2	365.4	2.3	832.3	13.7	24.5	51	14.00	14.06
6	710.6	385.9	977.3	83.4	287.4	521.2	14.53	14.21
8	-554.1	1407	940.3	21	87.5	121.7	14.43	14.17
9	-1452.2	-1141.6	-1764.1	136.6	611.6	527.2	11.45	11.47
10	212.9	499.8	714.6	26.3	63.4	79.9	13.96	13.95
11	-390.8	-1191	-1418.6	17.2	52.8	64.9	12.00*	11.81
19	764.6	1550.6	662.5	186.7	381.6	939.8	12.00*	13.89
26	-882.4	-26.6	-2191.3	290.1	962.3	1386.4	12.00*	11.04
27	389.3	-528.4	911.5	30.6	115.9	194.9	14.56	14.14
32	-260.6	-1450.2	-1344.7	18.2	75.6	169.4	12.00*	11.89
33	-108.4	270.8	452.1	32	45.1	88.7	13.50	13.68
35	532.7	129.4	-86.3	13.3	43.6	84.2	12.98	13.14
38	-174.2	-257.5	-105.4	25.1	54.7	79.6	13.33	13.13
39	-374.9	-317.5	-173.9	26.8	57.5	112.7	13.19	13.06
40	432.9	-751.4	835	19.7	51.5	77.6	13.97	14.07
42	200.6	-592	663.2	36.2	128.3	136.7	13.46	13.89
43	-982.5	-1446.5	-1020.1	40.4	76.6	188.3	12.00*	12.21
50	286.4	2195.2	942.9	144.2	371.6	1250	14.50	14.17

The average epicentre difference was 0.33 km and the average difference in focal depths was 1.4 km.

Figure A.24: projection of the relocated Ladysmith aftershocks, using MAXSEP 2 & V2

Figure A.25: The epicentral distribution of Ladysmith earthquake aftershocks using V2

Figure A.25 displays the distribution of epicentres obtained from the hypoDD using velocity model (2) and the GSC's catalog. The epicentres obtained by the GSC's catalog are displayed as the blue circles and the green-yellow diamonds show the relocated epicentres obtained by the hypoDD program (velocity model 2) and the movement direction is shown by arrows. Comparison between these two dataset shows that the average distance between catalog and relocated epicentres is 0.448 km, the maximum distance about 1.221 km (red arrow) and the minimum distance about 82 metres.

**Relocated Aftershocks in hypoDD for Ladysmith earthquake using both CNSN and
USTA data, MAXSEP=5, NITER=2 (Velocity model 3)**

Table A.22: The relocated hypocentres of the Ladysmith earthquake aftershocks, using both CNSN and USTA data, calculated from the hypoDD program using MAXSEP = 5, NITER = 2 & velocity model 3 (V3). * means depth was fixed.

ID	X	Y	Z	EX	EY	EZ	Depth	
							catalog	HypoDD
1	665.7	-916.9	76	39.8	188.2	126.9	13.50	13.84
2	298.3	-348.6	-459.2	39.4	186.7	129.7	14.00	13.31
4	-938.4	2571.6	832.9	91.9	615.6	332.3	14.53	14.60
5	932.3	-1741	-1333	40.5	192.1	138.7	12.00	12.44
6	691.3	-334.6	-1223.5	42.2	189.8	130.1	14.48	12.55
7	-498.2	-928.9	-3236.5	46.9	383.1	425.2	9.91	10.53
8	-594.9	1157.1	799.6	50.7	190.3	134.9	14.43	14.57
9	-1460.8	-966.5	-1412.6	38.6	184.5	143	11.45	12.36
10	41.4	-203.2	-314.2	39.4	187.7	127.1	13.96	13.45
11	-319.1	-1383	-2907.1	40.8	187.5	62.6	12.00*	10.86
19	-569.2	1215.7	-499.9	55.8	191.9	125.4	12.00*	13.27
21	1679.8	136.5	-1904	71.8	364.9	344.6	12.00*	11.86
27	526.6	-485.1	-513	39.5	188.6	127.6	14.56	13.26
32	-269.9	-1120.6	-1209.7	43	185.3	134.1	12.00*	12.56
33	-202.6	-365	-515.4	40	187.2	128.4	13.50	13.25
35	239.1	-45.1	-283.3	39.5	188.3	125.7	12.98	13.49
38	-180.2	-295.2	-528.3	39.3	187.2	127.6	13.33	13.24
39	-331	-645.2	-905.8	40.7	188.4	130.6	13.19	12.86
40	-314.5	-2076.6	-4189.6	477.1	507.6	827.1	13.97	9.58
42	136.8	-166.4	-380.9	39.5	188.1	126.3	13.46	13.39
43	-842	-844.1	-1385.1	48.8	187.4	143.6	12.00*	12.38
44	929.2	708.4	2709.8	133.7	192.4	190.7	18.00	16.48
45	425.1	85.9	5087.8	245.3	553.3	3000.9	18.00	18.86
46	-362.3	932.8	2370.5	102.8	299.5	194.1	18.00	16.14
47	329.7	-742.2	4896.1	946.7	3320	4578.6	18.00	18.67
50	641	673.1	-1371.1	46.4	188.6	312.5	14.50	12.40

Figure A.26: projection of the relocated Ladysmith earthquake aftershocks, using MAXSEP 5 & velocity model 3 (V3)

Figure A.27: The epicentral distribution of Ladysmith aftershocks using the velocity model 3 (V3)

The distribution of epicentres obtained from the hypoDD using velocity model (3) and the GSC catalog is represented in Figure A.27. The epicentres obtained by the GSC's catalog are displayed as the blue circles and the plus symbols show the relocated epicentres obtained by the hypoDD program (velocity model 3) and the movement direction is shown by arrows. Comparison between these two dataset shows that the average distance between catalog and relocated epicentres is 0.629 km, the maximum distance about 1.930 km (red arrow) and the minimum distance about 102 metres.

**Relocated Aftershocks in hypoDD for Ladysmith earthquake using both CNSN and
USTA data, MAXSEP=5, NITER=2 (Velocity model 4)**

Table A.23: The relocated hypocentres of the Ladysmith earthquake aftershocks, using both CNSN and USTA data, calculated from the hypoDD program using MAXSEP = 5, NITER = 2 & velocity model 4 (V4). * means depth was fixed.

ID	X	Y	Z	EX	EY	EZ	Depth	
							catalog	HypoDD
1	2173.9	893.2	2466.1	1178.7	1099.1	1444.7	13.50	16.24
2	1732.7	1459.6	1445.8	1175.4	1085.6	1477.6	14.00	15.21
4	223.7	4802.5	2958.9	4080.4	51897	5269.3	14.53	16.73
5	2441.3	-334.7	281.6	1182	1103.7	1536.5	12.00	14.05
6	2177.7	1345.3	73.7	1178	1090.3	1448.7	14.48	13.84
8	798.8	3473.3	2994.1	1196	1081.5	1495.2	9.91	16.76
9	459.7	-415.1	-77.6	2860.8	13166.5	10467.2	14.43	13.69
10	1560.3	1706.6	1671.3	1177.4	1086	1475.5	11.45	15.44
11	1580.7	585.9	510.2	1173.8	1079.3	1573	13.96	14.28
19	1488.3	2415.9	1494.5	1164.2	1075.7	1447.9	12.00*	15.26
21	695.5	7654.2	9212.2	3450	7592.8	12314.2	12.00*	22.98
27	1989.4	1315.8	1354.2	1175.8	1091.1	1454.9	12.00*	15.12
32	1502	473.6	838.9	1182.5	1076.1	1570.8	14.56	14.61
33	1330.6	1564.9	1454.1	1176	1083.8	1509.2	12.00*	15.22
35	1728.3	1673.5	1589	1176.2	1086.5	1466.1	13.50	15.36
38	1305.2	1456.2	1308.9	1174.9	1083.6	1519.7	12.98	15.08
39	1035.2	1327	1174.2	1170.6	1076.7	1573.7	13.33	14.94
42	1612.9	1329.2	1412	1177	1085.4	1493.8	13.19	15.18
43	746.9	962	907	23230.6	7541	43014.9	13.46	14.68
44	-85806.4	15774	-15.4	30230.6	38225.7	13254.1	12.00*	13.75
45	1265.6	1674.9	2469.7	1175.1	1090.4	1377.4	18.00	16.24
46	-8986.5	-28027.7	-8223.5	7021.7	24013.6	9577.7	18.00	5.55
47	1489.2	3569.4	-12056	1071.5	4126.6	28342.3	18.00	1.71

Figure A.28: projection of the relocated Ladysmith earthquake aftershocks, using MAXSEP 5 & velocity model 4 (V4)

Figure A.29: The epicentral distribution of Ladysmith aftershocks using the velocity model 4 (V4)

The distribution of epicentres obtained from the hypoDD using velocity model (4) and the GSC's catalog is represented in Figure A.29. The epicentres obtained by the GSC's catalog are displayed as the blue circles and the pink triangles show the relocated epicentres obtained by the hypoDD program (velocity model 4) and the movement direction is shown by arrows. Comparison between these two dataset shows that the average distance between catalog and relocated epicentres is 2.614 km, the maximum distance about 7.527 km (red arrow) and the minimum distance about 1.488 km. the relocated events using this model have been systematically shifted.

**Relocated Aftershocks in hypoDD for Ladysmith earthquake using both CNSN and
USTA data, MAXSEP=5, NITER=2 (Velocity model 5)**

Table A.24: The relocated hypocentres of the Ladysmith earthquake aftershocks, using both CNSN and USTA data, calculated from the hypoDD program using MAXSEP = 5, NITER = 2 & velocity model 5 (V5). * means depth was fixed.

ID	X	Y	Z	EX	EY	EZ	Depth	
							catalog	HypoDD
1	576.7	-687.6	837.2	35.3	58.3	35.8	13.50	14.61
2	237.9	73.7	397.4	35.6	58.8	39	14.00	14.17
4	-1061.9	3198.6	1707.2	47.8	117.3	40.3	14.53	15.48
5	874.8	-1644.8	-863.3	36.8	70.8	62.5	12.00	12.91
6	603.3	-318.2	-553.6	37.3	57.9	37.1	14.48	13.22
7	-176.3	-2933.4	-4847.1	189.9	616.3	609.3	9.91	8.92
8	-537.8	1989.3	1602	41.5	63.3	30.9	14.43	15.37
9	-1140.3	-809	-769.1	36.8	67.3	53	11.45	13.00
10	54.2	246.2	562.4	35.4	59.7	37.7	13.96	14.33
11	129.1	-1078.7	-1528.5	36.1	57.7	120.2	12.00*	12.24
19	-320.4	1053.6	137.7	45	65.3	35.8	12.00*	13.91
21	1988.1	-458.8	-2576	162.1	305.7	673.8	12.00*	11.19
26	-360.2	-837.4	-2791.7	197.9	236.4	393.9	12.00*	10.98
27	494.7	153.5	810.3	35.5	57.9	38.4	14.56	14.58
32	25.7	-1155.8	-640.7	43.8	58.5	76.7	12.00*	13.13
33	-161.7	188.7	390.6	35.8	60	37.5	13.50	14.16
35	153.1	-135.4	-88.2	39.5	65.7	125.7	12.98	13.68
38	-197.7	45.3	221.4	35.6	59.5	40.8	13.33	13.99
39	-391	-378.6	-286.6	60.8	56.4	121.9	13.19	13.48
40	-762.8	-118.4	-2958.8	116.9	277.2	400	13.97	10.81
42	97.5	-95.9	271.2	35.9	59.5	40.6	13.46	14.04
43	-784.4	-667.4	-707.7	37.2	56.1	35.1	12.00*	13.06
44	768	1241.2	2919.4	74.2	153.1	161.6	18.00	16.69
45	102	111.2	2848	37.6	58.8	272.1	18.00	16.62
46	-600.6	1991.7	3116.3	78.1	288.6	132	18.00	16.89
47	289.5	-889.4	4832.8	458	627.4	332.3	18.00	18.60
50	89.3	1908.3	-2041	89.9	194.9	182.1	14.50	11.73

Figure A.30: projection of the relocated Ladysmith earthquake aftershocks, using MAXSEP 5 & velocity model 5 (V5)

Figure A.31: The epicentral distribution of Ladysmith aftershocks using the velocity model 5 (V5)

The distribution of epicentres obtained from the hypoDD using velocity model (5) and the GSC's catalog are represented in Figure A.31. The epicentres obtained by the GSC's catalog are displayed as the blue circles and the relocated epicentres obtained by the hypoDD program (velocity model 5) are shown by light brown squares and the movement direction is shown by arrows. Comparison between these two dataset shows that the average distance between catalog and relocated epicentres is 0.570 km; the maximum and minimum distances are about 1.385 and 0.064 km, respectively.

Relocated Aftershocks in hypoDD for Ladysmith earthquake using both CNSN and USTA data, MAXSEP=2, NITER=3 (Velocity model 1)

Table A.25: The relocated hypocentres of the Ladysmith earthquake aftershocks, using both CNSN and USTA data, calculated from the hypoDD program using MAXSEP = 2, NITER = 3 & velocity model 1 (V1). * means depth was fixed.

ID	X	Y	Z	EX	EY	EZ	Depth	
							catalog	HypoDD
1	803.9	-837.6	668.8	11.7	15.2	22.8	13.50	13.90
2	484.5	-138.8	454.5	8.5	17.3	18.6	14.00	13.69
6	818.1	53.9	92	86.7	53.8	88.1	14.48	13.32
9	-1132.8	-1396.1	-1337.7	36.7	77.9	95.3	11.45	11.89
10	284.1	265.4	692.6	13.8	48.4	52.4	13.96	13.92
11	58.8	-1226.5	-585.9	71.4	106.6	82.2	12.00*	12.65
27	563.8	-523.2	539.4	13.4	23.6	26.2	14.56	13.77
32	86.8	-1563.9	-1007.7	61.9	48	56.9	12.00*	12.22
33	27.7	28.1	460.6	11.4	31.4	26.4	13.50	13.69
35	625.5	-46.8	71.5	16.7	40.7	37	12.98	13.30
38	-4.4	-41.1	382.8	18.4	34.6	34.2	13.33	13.61
39	-238.5	-519.4	-115.3	10	23.1	22.9	13.19	13.12
42	311	-218.4	440	15	22	20.8	13.46	13.67
43	-738.1	-1455.4	-1437.2	10.7	19.9	21.1	12.00*	11.79

Figure A.32: projection of the relocated Ladysmith aftershocks, using MAXSEP 2 & NITER 3

Relocated Aftershocks in hypoDD for Ladysmith earthquake using both CNSN and USTA data, MAXSEP=5, NITER=3 (Velocity model 1)

Table A.26: The relocated hypocentres of the Ladysmith earthquake aftershocks, using both CNSN and USTA data, calculated from the hypoDD program using MAXSEP = 5, NITER = 3 & velocity model 1 (V1). * means depth was fixed.

ID	X	Y	Z	EX	EY	EZ	Depth	
							catalog	HypoDD
1	659.9	-773.1	328.7	4.5	7	8.2	13.50	14.10
2	295.4	-154.9	-79.8	5.5	12.7	11.5	14.00	13.69
4	-778.4	2908.3	994.3	10.4	21.2	11.1	14.53	14.76
5	813.4	-1317.3	-959.6	7.9	22.6	19.8	12.00	12.81
6	580.5	58.6	-524.1	6.6	19.4	18.8	14.48	13.24
7	-336.2	-1062.5	-2404.2	30.4	56.1	102.9	9.91	11.36
8	-653.5	1668.3	953.3	21.1	83.7	28.1	14.43	14.72
9	-1359.5	-525.1	-989.2	10	26.2	35.1	11.45	12.78
10	28.7	60.5	115.1	4.8	11	9.1	13.96	13.88
11	38.6	-1045.5	-1304.9	9.8	16.6	27	12.00*	12.46
19	-1115.8	1724.5	-649.6	17.3	19	13.9	12.00*	13.12
21	1574.8	1209.3	-1044	18.9	48.9	64.7	12.00*	12.73
26	-795.3	-895.8	-3081.1	39	187.3	225.3	12.00*	10.69
27	493.4	-318.5	110.9	6.4	16.5	16	14.56	13.88
32	-70.9	-1114.9	-1011.3	10.3	46.9	62	12.00*	12.76
33	-214.5	-89.4	-116.4	5.4	11.7	11.4	13.50	13.65
35	287.8	-65.8	-324.1	7.6	15	21.3	12.98	13.44
38	-213.9	-124.8	-205.6	6.4	13.4	17.2	13.33	13.56
39	-289.6	-444.2	-519.3	9.4	14.4	17.3	13.19	13.25
40	-226.8	-880.8	-2446.5	25.1	22.6	85.7	13.97	11.32
42	91.3	-108.8	-85.7	8.1	14.5	15	13.46	13.68
43	-717.5	-1181.9	-1597.7	10.9	17.2	21	12.00*	12.17
44	864.3	1334.2	3211	57.6	116.9	71.2	18.00	16.98
45	307.8	49.5	4013.1	41.5	32.2	84.2	18.00	17.78
46	-287.1	1376.7	3047.7	25.1	193	47.7	18.00	16.82
50	635.1	1461.5	117	98.2	290.5	171.5	14.50	13.89

Figure A.33: projection of the relocated Ladysmith earthquake aftershocks, using MAXSEP 5 & NITER 3

Relocated Aftershocks in hypoDD for Ladysmith earthquake using both CNSN and USTA data, MAXSEP=2, NITER=4 (Velocity model 1)

Table A.27: The relocated hypocentres of the Ladysmith earthquake aftershocks, using both CNSN and USTA data, calculated from the hypoDD program using MAXSEP = 2, NITER = 4 & velocity model 1 (V1).

ID	X	Y	Z	EX	EY	EZ	Depth	
							catalog	HypoDD
1	813.8	-836.5	697.6	0.3	0.7	0.6	13.50	13.93
2	479.8	-110.7	479.9	0.5	0.8	0.6	14.00	13.71
6	739.5	-13.8	34.8	1	0.6	1.8	14.48	13.27
10	298.1	261.2	735.4	0.8	2.2	1	13.96	13.97
27	589.8	-451.1	451	2.5	2.5	2.2	14.56	13.68
33	72.7	98.8	496.4	1.7	2	2.3	13.50	13.73
35	609.9	-158.6	20	1	2.8	0.7	12.98	13.25
38	-38.6	-54.9	286.5	0.7	0.4	0.5	13.33	13.52
39	-248	-483.6	-141.9	0.3	0.9	0.3	13.19	13.09
42	322.4	-212.3	418.8	0.3	1.7	0.3	13.46	13.65

Figure A.34: projection of the relocated Ladysmith aftershocks, using MAXSEP 2 & NITER 4

**Relocated Aftershocks in hypoDD for Ladysmith earthquake using both CNSN and
USTA data, MAXSEP=5, NITER=4 (Velocity model 1)**

Table A.28: The relocated hypocentres of the Ladysmith aftershocks, using both CNSN and USTA data, calculated from hypoDD program using MAXSEP = 5, NITER = 4 & velocity model 1 (V1). * means depth was fixed.

ID	X	Y	Z	EX	EY	EZ	Depth	
							catalog	HypoDD
1	664.1	-757.2	332.1	4.9	5.1	4.1	13.50	14.10
2	293.4	-156.9	-81.7	4	7.8	8.5	14.00	13.69
4	-792.9	2929.8	1001.2	6.9	28.6	13.3	14.53	14.77
5	828.9	-1326.6	-941.4	17	86.5	83.6	12.00	12.83
6	598.3	49.9	-523	9.2	16.4	14	14.48	13.25
8	-925.9	1516.9	811.6	159.5	105.3	97.8	14.43	14.58
9	-1359.2	-454.1	-954.1	27.4	65.8	28.4	11.45	12.81
10	40.5	72.8	115.8	6.8	11.1	10.5	13.96	13.88
11	52.7	-1026.9	-1312.7	6	7.9	9.8	12.00*	12.46
19	-1164.7	1760.2	-674	11.4	26.7	16.3	12.00*	13.09
21	1606.1	909.1	-1384.9	56.4	51.4	46	12.00*	12.38
27	581.1	-114.5	300.7	132.6	195.8	187.2	14.56	14.07
32	80.5	-1468.6	-1275.6	148.8	244.6	214.1	12.00*	12.49
33	-221.4	-85.9	-122.4	3.4	9.8	10.2	13.50	13.65
35	303.5	-18.6	-238.9	7.6	43.1	55.1	12.98	13.53
38	-227.2	-151.4	-241.3	6.1	12.4	10.8	13.33	13.53
39	-294.5	-419.3	-506.4	5	10.3	9.5	13.19	13.26
42	62.1	-129.5	-118.4	4.9	8.9	9.6	13.46	13.65
43	-744.5	-1215.3	-1632.9	6	11.2	13.9	12.00*	12.14
45	323.6	103.3	3883.9	17.9	40.7	28.8	18.00	17.65
46	-354.9	1066.7	3049.8	4.6	9.5	13.9	18.00	16.82
47	801.5	-2123.7	5492.7	13.2	14.7	20.7	18.00	19.26

Figure A.35: projection of the relocated Ladysmith aftershocks, using MAXSEP5 & NITER 4

Relocated Aftershocks in hypoDD for Ladysmith earthquake using both CNSN and USTA data, MAXSEP=2, NITER=5 (Velocity model 1)

Table A.29: The relocated hypocentres of the Ladysmith earthquake aftershocks, using both CNSN and USTA data, calculated from the hypoDD program using MAXSEP = 2, NITER = 5 & velocity model 1 (V1).

ID	X	Y	Z	EX	EY	EZ	Depth	
							catalog	HypoDD
1	726.6	-908.8	757.6	0	0	0	13.50	13.99
10	292.4	180	731.3	0	0	0	13.96	13.96
33	16.2	-12	474.7	0	0	0	13.50	13.71
35	442.5	111.5	-629.4	0	0	0	12.98	12.60
38	-149.7	-94.2	167.2	0	0	0	13.33	13.40
39	-332.5	-397.6	-164.7	0	0	0	13.19	13.07
42	235	-247.1	400.3	0	0	0	13.46	13.63

Figure A.36: projection of the relocated Ladysmith earthquake aftershocks, using MAXSEP 2 & NITER 5

APPENDIX B - FOCAL MECHANISM SOLUTIONS AND POLARITIES DATA

2013/01/16-A

Latitude: 46.04N

Longitude: 75.45W

Depth: 18.09 km

Magnitude: 3.5 (M_N)

Origin Time: 00:53:04 (UT)

(Source: the GSC catalog, except depths which are from this study)

Polarity Data

Station	Azimuth (°)	Take-off Angle (°)	First Motion	Station	Azimuth (°)	Take-off Angle (°)	First Motion
VABQ	215.5	-50.10	D	DPQ	70.6	49.10	C
GAC	183.6	-65.70	D	KGNO	202.4	49.10	+ *
ALFO	137.7	-74.50	C	BANO	240.0	49.10	D
ORIO	184.3	-75.10	D	BECQ	81.1	49.10	+ *
OTT	196.0	-76.80	D	DELO	225.6	49.10	+
WBO	173.5	-82.30	D	E52A	276.8	49.10	-
G55A	228.3	-81.90	D	D52A	295.1	49.10	+
E54A	287.7	-82.70	D	MOQ	107.4	49.10	+ *
PEMO	253.6	-82.90	D	G53A	248.3	49.10	+
CRLO	269.6	-83.10	D	I55A	221.4	49.10	+ *
D54A	323.0	-83.20	+ *	EEO	284.3	49.10	-
SADO	244.9	49.10	+ *	F52A	265.7	49.10	+ *
PLVO	228.8	49.10	+	BUKO	258.8	49.10	+ *
E53A	282.4	49.10	-	D51A	292.2	49.10	+ *
STUQ	80.8	49.10	D	E51A	281.0	49.10	-
FRNY	132.5	49.10	+	F51A	269.1	49.10	+ *
ALGO	267.5	49.10	- *				

Table B.1: Polarity data used to determine the focal mechanism solutions for event 2013/01/16-A, * means the data has been bandpass-filtered at 1 - 10 Hz.

Focal Mechanism Solutions

Not including emergent polarity picks

Polarities/Errors: P 013/01

There are no amplitude ratio data

The minimum, increment and maximum B axis trend are 0.00 5.00 355.00

The limits for the B axis plunge are 0.00 5.00 90.00

The limits for the angle of the A axis are 0.00 5.00 85.00

Dip	Strike	Rake	Pol: P	Dip	Strike	Rake	Pol: P
45.00	125.00	90.00	1.0	46.92	129.49	69.25	1.0
50.00	125.00	90.00	1.0	52.84	111.05	64.59	1.0
45.00	130.00	90.00	1.0	48.36	113.47	62.76	1.0
50.00	130.00	90.00	1.0	52.84	116.34	64.59	1.0
45.00	145.00	90.00	1.0	48.36	118.77	62.76	1.0
45.00	150.00	90.00	1.0	43.96	295.47	60.48	1.0
50.18	110.82	83.48	1.0	48.36	298.77	62.76	1.0
50.18	115.82	83.48	1.0	43.96	300.77	60.48	1.0
50.18	120.82	83.48	1.0	54.37	107.86	58.67	1.0
45.22	135.02	82.95	1.0	50.14	110.01	56.60	1.0
45.22	140.02	82.95	1.0	50.14	115.55	56.60	1.0
45.22	145.02	82.95	1.0	46.03	117.27	54.04	1.0
40.26	299.07	82.25	1.0	58.68	293.67	60.35	1.0
40.26	304.07	82.25	1.0	54.37	301.71	58.67	1.0
45.22	305.02	82.95	1.0	46.03	300.04	54.04	1.0
40.26	309.07	82.25	1.0	56.17	104.98	53.00	1.0
40.26	314.07	82.25	1.0	52.24	106.98	50.77	1.0
50.73	108.33	77.04	1.0	60.22	294.25	54.82	1.0
50.73	113.40	77.04	1.0	56.17	296.59	53.00	1.0
50.73	118.47	77.04	1.0	60.22	300.06	54.82	1.0
45.86	121.98	76.00	1.0	48.44	294.37	48.07	1.0
45.86	127.05	76.00	1.0	56.17	302.40	53.00	1.0
45.86	132.12	76.00	1.0	44.81	295.44	44.81	1.0
45.86	137.19	76.00	1.0	48.44	300.18	48.07	1.0
41.03	302.67	74.66	1.0	52.24	304.40	50.77	1.0
45.86	304.52	76.00	1.0	44.81	301.24	44.81	1.0
50.73	306.08	77.04	1.0	54.60	104.40	45.28	1.0
41.03	302.67	74.66	1.0	51.13	105.98	42.55	1.0
50.73	306.08	77.04	1.0	65.82	292.86	51.04	1.0
51.62	106.03	70.72	1.0	61.98	295.41	49.48	1.0
51.62	111.18	70.72	1.0	58.23	297.69	47.57	1.0
46.92	119.20	69.25	1.0	47.85	296.27	39.32	1.0
46.92	124.35	69.25	1.0	60.50	292.39	42.39	1.0

Total number solutions: 66

#misfits: 0

Comments:

Preferred solutions: solutions are similar, so the closest to mean is used.

Plane 1:	Strike: 304°	Dip: 52°	Rake: 51°
Plane 2:	Strike: 177°	Dip: 52°	Rake: 129°
P-axis:	Trend: 241°	Plunge: 0°	
T-axis:	Trend: 151°	Plunge: 60°	
B-axis:	Trend: 331°	Plunge: 30°	

The Seismograms from which polarity data were read are shown in Figure B.1 – B.17 and the focal mechanism solutions are plotted in Figure B.18. The seismograms have been bandpass-filtered at 1-10 Hz in D54A and ALGO stations.

Figure B.1

Figure B.2

Figure B.3

Figure B.4

Figure B.5

Figure B.6

Figure B.7

Figure B.8

Figure B.9

Figure B.10

Figure B.11

Figure B.12

Figure B.13 **Figure B.14**

Figure B.15

Figure B.16

Figure B.17

Figures B.1 to B.17: Seismograms from which polarity data were read (event 2013/01/16-A). X- axis represents time (seconds) measured from origin time and Y- axis shows amplitude in digital counts.

Figure B.18: Focal mechanism solutions for event 2013/01/16-A. Lower hemisphere projection, circles show impulsive compression, triangles show impulsive dilatation, plus symbols show emergent compression, minus symbols show emergent dilatation, P means P axes, T means T axes and B means B axes.

2013/01/16-B

Latitude: 46.05N

Longitude: 75.43W

Depth: 18.70 km

Magnitude: 3.0 (M_N)

Origin Time: 01:01:48 (UT)

(Source: the GSC catalog, except depths which are from this study)

Polarity Data

Station	Azimuth (°)	Take-off Angle (°)	First Motion	Station	Azimuth (°)	Take-off Angle (°)	First Motion
VABQ	215.0	-50.70	D	STUQ	81.2	49.10	D
GAC	184.2	-65.60	D	FRNY	132.9	49.10	C
ALFO	138.7	-74.10	D	DPQ	70.8	49.10	+
ORIO	184.7	-74.90	D	H55A	202.4	49.10	+ *
OTT	196.1	-76.60	D	KGNO	202.4	49.10	+
WBO	173.8	-81.10	D	BANO	239.8	49.10	+
G55A	228.0	-82.10	+	DELO	225.5	49.10	-
E54A	287.2	-82.40	D	D52A	294.8	49.10	-
PEMO	253.2	-82.70	D	E52A	276.6	49.10	+ *
CRLO	269.2	-82.90	D	G53A	248.1	49.10	+
D54A	322.6	-83.00	C	I55A	221.3	49.10	+ *
MNTQ	113.6	-83.10	+	EEO	284.0	49.10	+
PLVO	228.6	49.10	C	F52A	265.6	49.10	+ *
E53A	282.0	49.10	D	BUKO	258.6	49.10	+ *
H56A	201.6	49.10	+ *	D51A	292.0	49.10	+
SADO	244.8	49.10	-				

Table B.2: Polarity data used to determine the focal mechanism solutions for event 2013/01/16-B, * means the data has been bandpass-filtered at 1 - 10 Hz.

Focal Mechanism Solutions

Not including emergent polarity picks

Polarities/Errors: P 014/01

There are no amplitude ratio data

The minimum, increment and maximum B axis trend are 0.00 5.00 355.00

The limits for the B axis plunge are 0.00 5.00 90.00

The limits for the angle of the A axis are 0.00 5.00 85.00

Dip	Strike	Rake	Pol: P
51.62	327.18	70.72	1.0
52.84	312.22	64.59	1.0
52.84	317.52	64.59	1.0
52.84	322.81	64.59	1.0
54.37	307.24	58.67	1.0
58.68	310.28	60.35	1.0
54.37	312.78	58.67	1.0
58.68	315.82	60.35	1.0
56.17	308.21	53.00	1.0

Total number solutions: 9

#misfits: 0

Preferred solutions: solutions are similar, so the closest to mean is used.

Plane 1: Strike: 316° Dip: 59° Rake: 60°

Plane 2: Strike: 183° Dip: 42° Rake: 129°

P-axis: Trend: 67° Plunge: 9°

T-axis: Trend: 175° Plunge: 63°

B-axis: Trend: 332° Plunge: 25°

P nodal planes

P, T and B axes

Figure B.19: Focal mechanism solutions for event 2013/01/16-B. Lower hemisphere projection, the format is the same as for Figure B.18.

2013/04/15

Latitude: 45.781N

Longitude: 74.44W

Depth: 8.67 km

Magnitude: 3.1 (M_N)

Origin Time: 13:32:25 (UT)

(Source: the GSC catalog, except depths which are from this study)

Polarity Data

Station	Azimuth (°)	Take-off Angle (°)	First Motion	Station	Azimuth (°)	Take-off Angle (°)	First Motion
ALFO	244.2	-77.40	D	DPQ	51.4	-86.90	D
TRQ	349.6	-80.00	D	MOQ	106.2	-87.20	C
MNTQ	115.9	-83.00	D	G55A	252.6	49.10	+
GAC	264.3	-83.90	D	H56A	228.0	49.10	- *
ORIO	246.8	-84.60	D	PLVO	249.2	49.10	+
VABQ	279.0	-84.60	D	E54A	289.8	49.10	-
STUQ	60.4	-85.80	D	D54A	312.6	49.10	+
FRNY	147.4	-86.00	- *	E53A	286.0	49.10	-
LONY	185.2	-86.20	C	DELO	241.8	49.10	-
GRQ	310.4	-86.50	C *	D53A	301.1	49.10	+

Table B.3: Polarity data used to determine the focal mechanism solutions for event 2013/04/15,

* means the data has been bandpass-filtered at 1 - 10 Hz.

Focal Mechanism Solution

Not including emergent polarity picks

Polarities/Errors: P 011/01

There are no amplitude ratio data

The minimum, increment and maximum B axis trend are 0.00 5.00 355.00

The limits for the B axis plunge are 0.00 5.00 90.00

The limits for the angle of the A axis are 0.00 5.00 85.00

Dip	Strike	Rake	Pol: P
85.00	245.00	-90.00	1.0
75.06	283.66	84.82	1.0
80.15	125.01	79.85	1.0
10.00	97.61	0.00	1.0
10.00	102.68	0.00	1.0
10.00	107.75	0.00	1.0
11.17	106.36	-26.30	1.0
11.17	111.43	-26.30	1.0
60.50	283.29	78.49	1.0
65.41	284.38	78.99	1.0
85.17	101.56	74.95	1.0
85.17	116.99	74.95	1.0
80.34	120.82	74.78	1.0
80.34	125.96	74.78	1.0
90.00	100.59	70.00	1.0
85.30	98.87	69.93	1.0
90.00	105.88	70.00	1.0
85.30	104.17	69.93	1.0
80.61	118.31	69.72	1.0
85.30	120.05	69.93	1.0
75.92	121.82	69.35	1.0
80.61	123.61	69.72	1.0
75.92	127.12	69.35	1.0
80.61	128.90	69.72	1.0
90.00	99.69	65.00	1.0
85.47	103.11	64.92	1.0
80.95	106.51	64.66	1.0
80.95	117.58	64.66	1.0
76.43	120.92	64.23	1.0
71.94	124.18	63.61	1.0
67.48	127.31	62.77	1.0

85.67	102.01	59.91	1.0
81.35	105.28	59.62	1.0
68.53	120.42	57.50	1.0
81.82	104.06	54.59	1.0

Total number solutions: 35

#misfits: 0

Comments: solutions cannot be used.

Preferred solutions: undefined focal mechanism. It is likely thrust but the accurate orientation cannot be defined.

Nodal planes: cannot be determined

P-axis: the orientation is not well determined but it seems the solutions are dispersed mainly in SW quadrant and some in SE and NE quadrants. Plunge cannot be determined.

T-axis: the orientation is not well determined but it seems the solutions are dispersed in NNW and some in SE and NNE quadrants. Plunge is estimated approximately 40° (moderate).

B-axis: the orientation is not well determined but it seems the solutions are dispersed mainly in SE and some in SW quadrants. Plunge is estimated approximately 10° - 25° (shallow).

Comment: Since this event resulted in a large number of options, I re-ran the program using the emergent picks and entered each impulsive arrival twice. The obtained solutions are more likely to be a believable solution.

Figure B.20: Focal mechanism solutions for event 2013/04/15. Lower hemisphere projection, the format is the same as for Figure B.18.

2013/05/17-A

Latitude: 45.74N

Longitude: 76.34W

Depth: 12.73 km

Magnitude: 5.2 (M_N)

Origin Time: 13:43:23 (UT)

(Source: the GSC catalog, except depths which are from this study)

Polarity Data

Station	Azimuth (°)	Take-off Angle (°)	First Motion	Station	Azimuth (°)	Take-off Angle (°)	First Motion
F55A	356.9	-40.10	C	G53A	249.8	49.10	D
LSQ1	68.6	-51.40	D	I55A	212.5	49.10	D
VABQ	71.7	-78.00	D	PECO	194.6	49.10	D
G55A	208.7	-78.30	D	D52A	311.6	49.10	C
OTT	127.7	-78.40	C	MNTQ	96.1	49.10	D
GAC	92.9	-79.30	D	F52A	272.6	49.10	+ *
PEMO	264.9	-79.80	D	EEO	296.5	49.10	C
ORIO	115.8	-80.00	D	FRNY	113.9	49.10	D
CRLO	292.9	-81.70	D	BUKO	263.3	49.10	D
PLVO	216.7	-82.50	D	SADO	244.9	49.10	D
E54A	320.2	-82.80	C	E51A	291.1	49.10	C
GRQ	21.0	-83.00	D	STUQ	74.8	49.10	D
ALFO	95.6	-83.60	D	D51A	303.9	49.10	C
WBO	134.0	-83.80	C	F51A	275.6	49.10	+ *
E53A	305.4	-84.20	C	VLDQ	339.0	49.10	C
H56A	177.0	-84.30	+ *	DPQ	67.9	49.10	-
ALGO	280.9	-84.60	D	BECQ	75.9	49.10	-
H55A	206.9	-85.10	D	MOQ	97.0	49.10	+
BANO	237.8	-85.10	D	EFO	219.8	49.10	D
TRQ	68.3	-85.10	D	BINY	175.7	49.10	D
D54A	351.4	-85.40	C	SUNO	286.4	49.10	C
KGNO	184.1	-85.70	D	PKME	92.9	49.10	D
DELO	217.0	-85.70	D	MALO	333.0	49.10	C
D53A	325.5	49.10	C	KLBO	263.4	49.10	C
LONY	131.3	-86.10	+	NCB	138.8	49.10	C
E52A	289.6	49.10	C				

Table B.4: Polarity data used to determine the focal mechanism solutions for event 2013/05/17-A, * means the data has been bandpass-filtered at 1 - 10 Hz.

Focal Mechanism Solution

Not including emergent polarity picks

Polarities/Errors: P 044/02

There are no amplitude ratio data

The minimum, increment and maximum B axis trend are 0.00 5.00 355.00

The limits for the B axis plunge are 0.00 5.00 90.00

The limits for the angle of the A axis are 0.00 5.00 85.00

Dip	Strike	Rake	Pol: P
54.37	130.01	58.67	2.0
52.24	124.40	50.77	2.0

Total number solutions: 2

#misfits:

Preferred solutions: solutions are similar, so one of them is used.

Plane 1: Strike: 130° Dip: 54° Rake: 59°

Plane 2: Strike: 356° Dip: 46° Rake: 126°

P-axis: Trend: 242° Plunge: 5°

T-axis: Trend: 341° Plunge: 65°

B-axis: Trend: 150° Plunge: 25°

Comment: solution is similar to the previously published studies (Bent *et al.*, 2015).

Figure B.21: Focal mechanism solutions for event 2013/05/17-A. Lower hemisphere projection, the format is the same as for Figure B.18.

2013/05/17-B

Latitude: 45.75N

Longitude: 76.35W

Depth: 13.55 km

Magnitude: 4.1 (M_N)

Origin Time: 13:53:55 (UT)

(Source: the GSC catalog, except depths which are from this study)

Polarity Data

Station	Azimuth (°)	Take-off Angle (°)	First Motion	Station	Azimuth (°)	Take-off Angle (°)	First Motion
F55A	357.4	-36.30	C	E53A	305.1	-83.80	D
LSQ1	71.4	-49.40	D	H56A	177.0	-84.00	+
VABQ	72.5	-77.30	D	ALGO	280.6	-84.20	+
G55A	208.3	-77.60	D	BANO	237.6	-84.80	D
GAC	93.6	-78.70	D	H55A	206.7	-84.80	- *
PEMO	264.3	-79.10	D	TRQ	68.6	-84.80	D
ORIO	116.3	-79.40	D	D54A	351.4	49.10	C
CRLO	292.4	81.10	D *	KGNO	184.0	49.10	+
PLVO	216.4	82.00	D	DELO	216.8	49.10	D
E54A	320.0	82.03	-	D53A	325.4	49.10	-
GRQ	21.2	-82.50	D	MNTQ	96.3	49.10	D
ALFO	95.9	-83.20	D	STUQ	75.0	49.10	D
WBO	134.2	-83.40	C	D51A	303.8	49.10	+ *

Table B.5: Polarity data used to determine the focal mechanism solutions for event 2013/05/17-B, * means the data has been bandpass-filtered at 1 - 10 Hz.

Focal Mechanism Solution

Not including emergent polarity picks

Polarities/Errors: P 019/00

There are no amplitude ratio data

The minimum, increment and maximum B axis trend are 0.00 5.00 355.00

The limits for the B axis plunge are 0.00 5.00 90.00

The limits for the angle of the A axis are 0.00 5.00 85.00

Dip	Strike	Rake	Pol: P
45.86	137.19	76.00	0.0
46.92	129.49	69.25	0.0
46.92	134.63	69.25	0.0
46.92	139.77	69.25	0.0
52.84	126.93	64.59	0.0
48.36	129.35	62.76	0.0
52.84	132.22	64.59	0.0
48.36	134.65	62.76	0.0
52.84	137.52	64.59	0.0
43.96	136.65	60.48	0.0
48.36	139.94	62.76	0.0
54.37	124.47	58.67	0.0
58.68	127.52	60.35	0.0
50.14	126.63	56.60	0.0
54.37	130.01	58.67	0.0
58.68	133.05	60.35	0.0
46.03	128.34	54.04	0.0
50.14	132.17	56.60	0.0
54.37	135.55	58.67	0.0
46.03	133.88	54.04	0.0
50.14	137.71	56.60	0.0
46.03	139.42	54.04	0.0
56.17	128.21	53.00	0.0
60.22	131.67	54.82	0.0
48.44	125.98	48.07	0.0
52.24	130.21	50.77	0.0
56.17	134.01	53.00	0.0
60.22	137.48	54.82	0.0
48.44	131.79	48.07	0.0
52.24	136.02	50.77	0.0
44.81	132.86	44.81	0.0
48.44	137.60	48.07	0.0
44.81	138.66	44.81	0.0
58.23	126.84	47.57	0.0

54.60	128.81	45.28	0.0
58.23	132.94	47.57	0.0
51.13	130.39	42.55	0.0
54.60	134.91	45.28	0.0
47.85	131.52	39.32	0.0
51.13	136.49	42.55	0.0
44.81	132.14	35.53	0.0
47.85	137.63	39.32	0.0

Total number solutions: 42

#misfits:

Comments: the resulted solutions are different from previously published study (Bent *et al.*, 2015) in terms of strike but with the similar dip and rake.

Preferred solutions: solutions are similar, so the closest to mean is used.

Plane 1: Strike: 138° Dip: 50° Rake: 57°

Plane 2: Strike: 3° Dip: 50° Rake: 123°

P-axis: Trend: 71° Plunge: 0°

T-axis: Trend: 341° Plunge: 65°

B-axis: Trend: 161° Plunge: 25°

Figure B.22: Focal mechanism solutions for event 2013/05/17-B. Lower hemisphere projection, The format is the same as for Figure B.18.

2013/05/17-C

Latitude: 45.75N

Longitude: 76.35W

Depth: 13.14 km

Magnitude: 3.2 (M_N)

Origin Time: 20:15:17 (UT)

(Source: the GSC catalog, except depths which are from this study)

Polarity Data

Station	Azimuth (°)	Take-off Angle (°)	First Motion	Station	Azimuth (°)	Take-off Angle (°)	First Motion
F55A	358.6	-36.80	C	BANO	237.5	49.10	+*
G55A	208.1	-78.00	D	H55A	206.6	-84.90	+
VABQ	72.6	-77.70	D	TRQ	68.7	49.10	D
OTT	128.2	-78.20	+ *	D54A	351.5	49.10	-
PEMO	264.2	-79.40	D	DELO	216.7	49.10	-
GAC	93.6	-79.00	D	D53A	325.5	49.10	+
ORIO	116.3	-79.80	D	LONY	131.4	49.10	+
CRLO	292.4	-81.40	D	E52A	289.4	49.10	+
PLVO	216.3	-82.30	D	I55A	212.2	49.10	+
E54A	320.0	-82.50	+	D52A	311.5	49.10	+
GRQ	21.3	-82.70	D	EEO	296.6	49.10	-
ALFO	96.0	-83.50	D	BUKO	263.0	49.10	+
E53A	305.1	-83.90	-	E51A	290.9	49.10	+
H56A	176.9	-84.10	- *	F51A	275.5	49.10	+ *
ALGO	280.6	-84.40	D	DPQ	68.1	49.10	+

Table B.6: Polarity data used to determine the focal mechanism solutions for event 2013/05/17-C, * means the data has been bandpass-filtered at 1 - 10 Hz.

Focal Mechanism Solution

Not including emergent polarity picks

Polarities/Errors: P 012/00 There are no amplitude ratio data

The minimum, increment and maximum B axis trend are 0.00 5.00 355.00

The limits for the B axis plunge are 0.00 5.00 90.00

The limits for the angle of the A axis are 0.00 5.00 85.00

Dip Strike Rake Pol: P

30.00 135.00 90.00 4.0

25.00 140.00 90.00 4.0

30.00 140.00 90.00 4.0

55.15 311.51 83.90 4.0

60.13 312.12 84.23 4.0

65.10 312.67 84.49 4.0

70.08 313.18 84.68 4.0

60.13 317.12 84.23 4.0

65.10 317.67 84.49 4.0

70.08 318.18 84.68 4.0

75.06 318.66 84.82 4.0

41.03 130.28 74.66 4.0

Total number solutions: 12 #misfits: 0

Preferred solutions: solutions are similar.

Plane 1: Strike: 140° Dip: 25° Rake: 90°

Plane 2: Strike: 320° Dip: 65° Rake: 90°

P-axis: Trend: 50° Plunge: 20°

T-axis: Trend: 230° Plunge: 70°

B-axis: Trend: 140° Plunge: 0°

*** Comment: I re-ran Focmec (with 4 allowed P polarity errors) and got 12 solutions which are not very different from previous results but the uncertainty is lower.

Figure B.23: Focal mechanism solutions for event 2013/05/17-C. Lower hemisphere projection, the format is the same as for Figure B.18.

2013/05/21

Latitude: 45.44N

Longitude: 74.20W

Depth: 17.74 km

Magnitude: 3.4 (M_N)

Origin Time: 20:43:01 (UT)

(Source: the GSC catalog, except depths which are from this study)

Polarity Data

Station	Azimuth (°)	Take-off Angle (°)	First Motion	Station	Azimuth (°)	Take-off Angle (°)	First Motion
MNTQ	80.9	-68.70	D	G55A	265.0	49.10	+
ALFO	291.8	-72.90	C	PEMO	277.5	49.10	+
FRNY	144.2	-77.80	+	E54A	296.6	49.10	D
LONY	198.6	-79.50	C	D54A	316.0	49.10	+ *
WBO	240.6	-79.70	D	DELO	250.5	49.10	-
ORIO	271.4	-80.20	D	E53A	292.5	49.10	-
GAC	286.9	-80.30	+	I55A	245.0	49.10	+
STUQ	41.3	-82.10	D	D53A	305.3	49.10	+
MOQ	94.5	-83.40	C	SADO	261.0	49.10	+ *
DPQ	38.0	49.10	+	F51A	279.0	49.10	-
H56A	240.7	49.10	-*				

Table B.7: Polarity data used to determine the focal mechanism solutions for event 2013/05/21,
* means the data has been bandpass-filtered at 1 - 10 Hz.

Focal Mechanism Solution

Not including emergent polarity picks

Polarities/Errors: P 008/01

There are no amplitude ratio data

The minimum, increment and maximum B axis trend are 0.00 5.00 355.00

The limits for the B axis plunge are 0.00 5.00 90.00

The limits for the angle of the A axis are 0.00 5.00 85.00

Total number solutions: 530

#misfits: 0

Comments: can't constrain because there are 530 solutions that fit the data equally well

Preferred solutions: Undefined focal mechanism. It could be strike-slip or thrust fault but the accurate orientation cannot be defined.

Nodal planes: cannot be determined

P-axis: the orientation is not well determined but it seems the solutions are dispersed in every azimuth but only SE quadrant can be ruled out. Plunge cannot be determined.

T-axis: the orientation is not well determined but it seems the solutions are mainly dispersed in every azimuth but only SW quadrant can be ruled out. Plunge is estimated moderate, approximately 45°-55°, (near-horizontal in NW and SE).

B-axis: the orientation is not well determined but it seems the solutions are dispersed in every azimuth but only NW quadrant can be ruled out. Plunge is estimated nearly horizontal.

Figure B.24: Focal mechanism solutions for event 2013/05/21. Lower hemisphere projection, the format is the same as for Figure B.18.

2013/05/24

Latitude: 47.12N

Longitude: 76.78W

Depth: 17.14 km

Magnitude: 3.6 (M_N)

Origin Time: 07:08:31 (UT)

(Source: the GSC catalog, except depths which are from this study)

Polarity Data

Station	Azimuth (°)	Take-off Angle (°)	First Motion	Station	Azimuth (°)	Take-off Angle (°)	First Motion
D54A	70.1	-29.00	D	OTT	156.6	49.10	+ *
D53A	266.4	-76.30	C *	ORIO	151.9	49.10	C *
E54A	202.5	-78.30	C *	E51A	253.4	49.10	-
E53A	219.7	-80.90	-	ALFO	138.1	49.10	+
D52A	263.1	-82.20	D	PLVO	185.8	49.10	+ *
CRLO	201.3	-82.40	D	F52A	233.9	49.10	- *
F55A	167.1	-83.30	+	BANO	201.3	49.10	+
ALGO	217.5	-84.00	C	G53A	213.4	49.10	+ *
LSQ1	161.9	-83.70	D	WBO	153.3	49.10	+ *
PEMO	192.9	-84.10	D	BUKO	228.2	49.10	+
E52A	237.8	49.10	-	H56A	171.7	49.10	+ *
EEO	253.8	-84.60	D	SADO	106.6	49.10	-
D51A	269.9	49.10	+ *	DELO	193.1	49.10	+ *
GAC	147.3	49.10	C	DPQ	97.7	49.10	+
G55A	178.8	49.10	+ *				

Table B.8: Polarity data used to determine the focal mechanism solutions for event 2013/05/24,
* means the data has been bandpass-filtered at 1 - 10 Hz.

Focal Mechanism Solution

Not including emergent polarity picks

Polarities/Errors: P 012/01 There are no amplitude ratio data

The minimum, increment and maximum B axis trend are 0.00 2.00 355.00

The limits for the B axis plunge are 0.00 2.00 90.00

The limits for the angle of the A axis are 0.00 2.00 85.00

Dip	Strike	Rake	Pol: P
8.94	337.02	26.40	1.0
9.99	347.40	36.64	1.0
11.30	355.62	44.72	1.0
12.78	2.06	51.02	1.0
8.94	339.03	26.40	1.0
9.99	349.42	36.64	1.0
11.30	357.64	44.72	1.0
12.78	4.07	51.02	1.0
8.94	341.05	26.40	1.0
9.99	351.43	36.64	1.0
11.30	359.65	44.72	1.0
12.78	6.09	51.02	1.0
8.94	343.07	26.40	1.0
9.99	353.45	36.64	1.0
11.30	1.67	44.72	1.0
12.78	8.11	51.02	1.0
8.94	345.08	26.40	1.0
9.99	355.47	36.64	1.0
11.30	3.69	44.72	1.0
8.24	334.51	13.95	1.0
8.94	347.10	26.40	1.0
9.99	357.48	36.64	1.0
11.30	5.70	44.72	1.0
8.24	336.53	13.95	1.0
8.94	349.12	26.40	1.0
9.99	359.50	36.64	1.0
8.24	338.54	13.95	1.0
8.94	351.13	26.40	1.0
8.24	340.56	13.95	1.0
8.94	353.15	26.40	1.0
8.24	342.58	13.95	1.0
8.94	355.17	26.40	1.0
8.24	344.59	13.95	1.0
8.24	346.61	13.95	1.0
8.24	348.63	13.95	1.0
12.78	347.52	38.28	1.0
12.78	355.64	38.28	1.0

11.65	349.87	30.66	1.0
12.78	357.67	38.28	1.0
10.76	342.64	21.58	1.0
11.65	351.90	30.66	1.0
12.78	359.69	38.28	1.0
10.76	344.67	21.58	1.0
11.65	353.92	30.66	1.0
12.78	1.72	38.28	1.0
10.76	346.70	21.58	1.0
11.65	355.95	30.66	1.0
10.20	338.17	11.20	1.0
10.76	348.73	21.58	1.0
11.65	357.98	30.66	1.0
10.20	340.19	11.20	1.0
10.76	350.76	21.58	1.0
10.20	342.22	11.20	1.0
10.76	352.79	21.58	1.0
10.20	344.25	11.20	1.0
10.20	346.28	11.20	1.0
10.00	338.97	0.00	1.0

Total number solutions: 57 #misfits: 0, Comments: the fault plane solution looks unusual for this region. Preferred solutions: solutions are similar, so the closest to mean is used.

Plane 1: Strike: 6° Dip: 13° Rake: 51°

Plane 2: Strike: 226° Dip: 80° Rake: 98°

P-axis: Trend: 309° Plunge: 35°

T-axis: Trend: 146° Plunge: 54°

B-axis: Trend: 44° Plunge: 8°

Figure B.25

Figure B.26

Figure B.27

Figure B.28

Figure B.29

Figure B.30

Figure B.31 **Figure B.32**

Figure B.33

Figure B.34

Figure B.35

Figure B.36

Figure B.37 **Figure B.38**

Figure B.39

Figure B.40

Figure B.41 **Figure B.42**

Figure B.43 **Figure B.44**

Figure B.45

Figure B.46

Figure B.47 **Figure B.48**

Figure B.49 **Figure B.50**

Figure B.51

Figures B.25 to B.51: Seismograms from which polarity data were read (event 2013/05/24). X- axis represents time (seconds) measured from origin time and Y- axis shows amplitude in digital counts.

Figure B.52: Focal mechanism solutions for event 2013/05/24. Lower hemisphere projection, the format is the same as for Figure B.18.

2013/05/30

Latitude: 45.75N

Longitude: 76.35W

Depth: 12.89 km

Magnitude: 3.7 (M_N)

Origin Time: 05:34:58 (UT)

(Source: the GSC catalog, except depths which are from this study)

Polarity Data

Station	Azimuth (°)	Take-off Angle (°)	First Motion	Station	Azimuth (°)	Take-off Angle (°)	First Motion
LDSQ	174.2	-16.40	C	DELO	216.6	-85.60	D
F55A	0.4	-36.90	C	KGNO	183.8	49.10	-
G55A	207.7	-78.20	D	D53A	325.5	49.10	+
OTT	128.1	-78.50	D *	E52A	289.4	49.10	-
GAC	93.7	-79.30	D	G53A	249.5	49.10	-
PEMO	264.0	-79.60	D	I55A	212.1	49.10	+ *
ORHO	116.6	-79.70	D	PECO	194.4	49.10	+
ORIO	116.3	-80.00	D	D52A	311.5	49.10	C
CRLO	292.4	-81.50	D	MNTQ	96.4	49.10	-
PLVO	216.0	-82.40	D	F52A	272.4	49.10	+
E54A	320.1	-82.70	-	EEO	296.3	49.10	-
E53A	305.1	-84.00	D	FRNY	114.1	49.10	+
ALFO	96.0	-83.60	D	BUKO	263.0	49.10	+
ALGO	280.5	-84.50	D	SADO	244.6	49.10	-
H56A	176.7	-84.30	+	E51A	290.9	49.10	-
BANO	237.4	-85.00	D	STUQ	75.1	49.10	+
H55A	206.5	-85.10	- *	F51A	275.4	49.10	-
D54A	351.6	-85.30	+	MOQ	97.1	49.10	+ *

Table B.9: Polarity data used to determine the focal mechanism solutions for event 2013/05/30,

* means the data has been bandpass-filtered at 1 - 10 Hz.

Focal Mechanism Solution

Not including emergent polarity picks

Polarities/Errors: P 016/00

There are no amplitude ratio data

The minimum, increment and maximum B axis trend are 0.00 5.00 355.00

The limits for the B axis plunge are 0.00 5.00 90.00

The limits for the angle of the A axis are 0.00 5.00 85.00

Total number solutions: 761

#misfits: 0

Comments: Undefined focal mechanism. It is likely thrust fault but the accurate orientation cannot be defined.

Preferred solutions:

Nodal planes: cannot be determined

P-axis: the orientation is not well determined but the solutions are dispersed in ENE and ESE and SW octants. Plunge is estimated approximately 0° - 30° (shallow to moderate).

T-axis: the orientation is not well determined; near vertical in every azimuth.

B-axis: the orientation is not well determined but the solutions are dispersed in NNW, SSE and some in NE and SW quadrants. Plunge is estimated approximately 0° - 35° , (shallow to moderate).

P nodal planes

P, T and B axes

Figure B.53: Focal mechanism solutions for event 2013/05/30. Lower hemisphere projection, the format is the same as for Figure B.18.

2013/06/30

Latitude: 45.75N

Longitude: 76.35W

Depth: 13.85 km

Magnitude: 3.1 (M_N)

Origin Time: 08:40:46 (UT)

(Source: the GSC catalog, except depths which are from this study)

Polarity Data

Station	Azimuth (°)	Take-off Angle (°)	First Motion	Station	Azimuth (°)	Take-off Angle (°)	First Motion
LDSQ	173.9	-15.50	C	D54A	351.6	49.10	+
F55A	0.5	-34.80	C	DELO	216.5	49.10	-
VABQ	72.9	-77.10	D	D53A	325.5	49.10	+
G55A	207.7	-77.40	C	LONY	131.4	-85.80	+ *
GAC	93.8	-78.50	D	G53A	2495	49.10	C
PEMO	264.0	-78.80	D	PECO	194.4	-86.20	-
CRLO	292.4	-80.90	-	D52A	311.5	49.10	+ *
PLVO	216.0	-81.90	+	F52A	272.4	49.10	+
E54A	320.1	-82.10	+	EEO	296.3	49.10	-
WBO	134.1	-83.30	-	BUKO	263.0	49.10	+
E53A	305.1	-83.60	-	SADO	244.6	49.10	+
H56A	176.7	-83.80	- *	E51A	290.9	49.10	+ *
ALGO	280.5	49.10	+	D51A	303.8	49.10	+
BANO	237.3	-84.60	-	F51A	275.4	49.10	-
H55A	206.5	49.10	+	DPQ	68.1	49.10	-
TRQ	68.8	-84.70	D	H52A	247.4	49.10	+ *
D50A	301.7	49.10	+	D49A	295.6	49.10	+

Table B.10: Polarity data used to determine the focal mechanism solutions for event 2013/06/30,

* means the data has been bandpass-filtered at 1 - 10 Hz.

Focal Mechanism Solution

Not including emergent polarity picks

Polarities/Errors: P 008/00

There are no amplitude ratio data

The minimum, increment and maximum B axis trend are 0.00 5.00 355.00

The limits for the B axis plunge are 0.00 5.00 90.00

The limits for the angle of the A axis are 0.00 5.00 85.00

Total number solutions: 537

#misfits:

Comments: can't constrain because there are 537 solutions that fit the data equally well

Preferred solutions: Undefined focal mechanism. It is likely thrust but the accurate orientation cannot be defined.

Nodal planes: cannot be determined

P-axis: solutions are dispersed in SE and NW quadrants. Plunge is estimated approximately 0° - 20° (near horizontal).

T-axis: the orientation is not well defined but the solutions are dispersed in NNE and SSW and NNW octants. Plunge is estimated approximately 65° - 90° (near vertical).

B-axis: the orientation is not well defined but the solutions are mainly dispersed in NNE octant and some solutions in SW, NNW. Plunge cannot be determined (shallow to moderate in SW).

Figure B.54: Focal mechanism solutions for event 2013/06/30. Lower hemisphere projection, the format is the same as for Figure B.18.

2013/09/04

Latitude: 46.65N

Longitude: 75.57W

Depth: 15.58 km

Magnitude: 3.1 (M_N)

Origin Time: 01:52:12 (UT)

(Source: the GSC catalog, except depths which are from this study)

Polarity Data

Station	Azimuth (°)	Take-off Angle (°)	First Motion	Station	Azimuth (°)	Take-off Angle (°)	First Motion
D55A	11.6	-68.20	C	G57A	165.1	49.10	-
E56A	109.4	-70.50	C	G58A	144.6	49.10	D
E55A	236.3	-70.70	-	ALGO	248.1	49.10	D *
D56A	56.2	-78.20	D	D58A	76.2	49.10	+
VABQ	181.7	-79.70	D	DPQ	88.9	49.10	+
D54A	303.1	-80.90	C	PLVO	213.2	49.10	C *
GAC	176.0	-81.80	C	F59A	112.1	49.10	D
F55A	212.8	-82.00	D	G54A	234.8	49.10	C
F57A	144.3	-82.50	+	BANO	225.6	49.10	+ *
E54A	258.3	-83.00	-	EEO	270.4	49.10	C *
D57A	73.0	-83.040	-	G53A	235.0	49.10	+
ORIO	177.9	-83.50	-	F52A	252.6	49.10	+
E53A	259.1	-84.60	D	E60A	94.7	49.10	+
D53A	286.2	49.10	C	SADO	233.9	49.10	+
PEMO	229.9	49.10	D	F61A	92.2	49.10	-
E58A	100.0	49.10	D				

Table B.11: Polarity data used to determine the focal mechanism solutions for event 2013/09/04,

* means the data has been bandpass-filtered at 1 - 10 Hz.

Focal Mechanism Solution

Not including emergent polarity picks

Polarities/Errors: P 017/02

There are no amplitude ratio data

The minimum, increment and maximum B axis trend are 0.00 5.00 355.00

The limits for the B axis plunge are 0.00 5.00 90.00

The limits for the angle of the A axis are 0.00 5.00 85.00

Dip Strike Rake Pol: P

48.36 101.59 -18.88 2.0

46.92 108.07 -14.51 2.0

52.84 111.54 -16.01 2.0

56.36 111.40 -10.27 2.0

57.39 114.34 -13.47 2.0

61.98 117.20 -11.17 2.0

Total number solutions: 6

#misfits: 0

Preferred solutions: solutions are similar.

Plane 1: Strike: 117° Dip: 62° Rake: -11°

Plane 2: Strike: 212° Dip: 80° Rake: -152°

P-axis: Trend: 78° Plunge: 27°

T-axis: Trend: 342° Plunge: 12°

B-axis: Trend: 230° Plunge: 60°

P nodal planes

P, T and B axes

Figure B.55: Focal mechanism solutions for event 2013/09/04. Lower hemisphere projection, the format is the same as for Figure B.18.

2013/10/20

Latitude: 45.62N

Longitude: 77.43W

Depth: 20.34 km

Magnitude: 3.6 (M_N)

Origin Time: 10:40:33 (UT)

(Source: the GSC catalog, except depths which are from this study)

Polarity Data

Station	Azimuth (°)	Take-off Angle (°)	First Motion	Station	Azimuth (°)	Take-off Angle (°)	First Motion
PEMO	67.1	-38.80	C	GAC	85.8	-82.40	- *
CRLO	5.7	-66.40	D	BUKO	263.3	-82.50	-
ALGO	308.2	-71.40	D *	I55A	187.1	-82.60	D
G54A	244.3	-70.20	C	D53A	353.0	49.10	D
G55A	125.6	-73.70	C	SADO	235.3	-82.90	D
PLVO	156.0	-73.90	D	D52A	333.9	49.10	D
BANO	210.0	-75.20	D	EEO	312.5	49.10	D
E53A	348.4	-76.70	D *	KGNO	153.9	49.10	+
F55A	74.0	-77.00	D	D54A	19.2	49.10	D
E54A	12.1	-77.60	D *	WBO	111.3	49.10	+
G53A	239.6	-79.30	-	F51A	281.0	49.10	-
H55A	170.3	-80.40	D	ALFO	88.8	49.10	-
DELO	186.6	-80.60	D *	G57A	105.8	49.10	+ *
OTT	100.0	-81.50	+	E56A	60.3	49.10	-
E55A	48.6	-81.80	D	F57A	83.3	49.10	- *
VABQ	76.8	-82.10	D	D55A	43.5	49.10	-
H53A	218.1	-82.10	D	E48A	286.3	49.10	+
ORIO	96.4	-82.40	-				

Table B.12: Polarity data used to determine the focal mechanism solutions for event 2013/10/20,

* means the data has been bandpass-filtered at 1 - 10 Hz.

Focal Mechanism Solution

Not including emergent polarity picks

Polarities/Errors: P 021/01

There are no amplitude ratio data

The minimum, increment and maximum B axis trend are 0.00 5.00 355.00

The limits for the B axis plunge are 0.00 5.00 90.00

The limits for the angle of the A axis are 0.00 5.00 85.00

Dip	Strike	Rake	Pol: P
30.00	65.00	90.00	1.0
55.15	241.51	83.90	1.0
60.13	242.12	84.23	1.0
65.10	242.67	84.49	1.0
65.10	247.67	84.49	1.0
50.18	260.82	83.48	1.0
65.41	238.75	78.99	1.0
55.61	241.52	77.85	1.0
60.50	242.73	78.49	1.0
50.73	250.30	77.04	1.0
55.61	251.66	77.85	1.0
50.73	255.37	77.04	1.0
55.61	256.73	77.85	1.0
50.73	260.44	77.04	1.0
51.62	255.18	70.72	1.0
46.92	258.06	69.25	1.0
48.36	251.12	62.76	1.0

Total number solutions: 17 #misfits: 0

Comments: the fault plane orientation looks unusual for this region.

Preferred solutions: solutions are similar, so the closest to mean is used.

Plane 1:	Strike: 242°	Dip: 56°	Rake: 78°
Plane 2:	Strike: 82°	Dip: 36°	Rake: 107°
P-axis:	Trend: 340°	Plunge: 10°	
T-axis:	Trend: 114°	Plunge: 76°	
B-axis:	Trend: 248°	Plunge: 10°

Figure B.56: Focal mechanism solutions for event 2013/10/20. Lower hemisphere projection, the format is the same as for Figure B.18.

2014/02/07

Latitude: 45.09N

Longitude: 73.65W

Depth: 12.19 km

Magnitude: 3.1 (M_N)

Origin Time: 15:45:05 (UT)

(Source: the GSC catalog, except depths which are from this study)

Polarity Data

Station	Azimuth (°)	Take-off Angle (°)	First Motion	Station	Azimuth (°)	Take-off Angle (°)	First Motion
FRNY	171.4	-67.30	+	VABQ	301.1	49.10	+
G58A	280.8	-69.60	+	DPQ	20.6	49.10	+
MNTQ	2.1	-74.90	-	E56A	326.6	49.10	-
LONY	234.9	-82.40	-	D57A	355.0	49.10	-
G60A	89.4	-83.30	+	F55A	292.2	49.10	-
G57A	271.0	-83.40	-	D58A	14.6	49.10	- *
F59A	38.4	-83.50	-	D56A	338.3	49.10	+
WBO	266.0	-84.60	D	G55A	275.3	49.10	+
TRQ	330.8	-85.10	-	D59A	32.7	49.10	+
E58A	11.2	-85.20	+	D55A	327.2	49.10	-
E57A	345.2	-85.40	+	D54A	315.5	49.10	+ *
GAC	295.9	-85.60	-	E53A	295.9	49.10	+
F60A	53.1	-85.70	- *				

Table B.13: Polarity data used to determine the focal mechanism solutions for event 2014/02/07,

* means the data has been bandpass-filtered at 1 - 10 Hz.

Focal Mechanism Solution

*** Including emergent polarity picks

Polarities/Errors: P 025/06

There are no amplitude ratio data

The minimum, increment and maximum B axis trend are 0.00 2.00 355.00

The limits for the B axis plunge are 0.00 2.00 90.00

The limits for the angle of the A axis are 0.00 2.00 85.00

Dip	Strike	Rake	Pol: P
78.27	160.67	77.74	6.0
78.36	158.02	75.70	6.0
76.42	159.57	75.59	6.0
76.42	161.63	75.59	6.0
74.49	163.18	75.46	6.0
76.42	163.70	75.59	6.0
76.55	160.04	73.54	6.0
76.55	162.12	73.54	6.0

Total number solutions: 8

Comments: I re-ran the Focmec and included the emergent data, the quality of obtained solution is poor and some of the polarities ($\sim$ one quarter) don't fit the solutions.

Preferred solutions: solutions are similar, so the closest to mean is used.

Plane 1:	Strike: 161°	Dip: 78°	Rake: 78°
Plane 2:	Strike: 28°	Dip: 17°	Rake: 136°
P-axis:	Trend: 261°	Plunge: 32°	
T-axis:	Trend: 55°	Plunge: 55°	
B-axis:	Trend: 163°	Plunge: 12°

P nodal planes

P, T and B axes

Figure B.57: Focal mechanism solutions for event 2014/02/07. Lower hemisphere projection, the format is the same as for Figure B.18.

2014/03/30

Latitude: 46.95N

Longitude: 76.46W

Depth: 18.57 km

Magnitude: 3.0 (M_N)

Origin Time: 03:47:15 (UT)

(Source: the GSC catalog, except depths which are from this study)

Polarity Data

Station	Azimuth (°)	Take-off Angle (°)	First Motion	Station	Azimuth (°)	Take-off Angle (°)	First Motion
D54A	327.1	-55.40	C *	G55A	186.1	49.10	D
E55A	150.4	-73.60	+	D57A	86.8	49.10	D *
D55A	83.7	-76.20	-	EEO	261.2	49.10	+
E54A	224.3	-76.90	+	G54A	216.7	49.10	C *
D53A	279.2	-79.00	C *	PLVO	192.8	49.10	+ *
E56A	111.9	-81.10	C *	ALFO	139.8	49.10	+
E53A	235.8	-80.50	-	G57A	150.3	49.10	+
F55A	176.0	-81.50	-	E51A	259.8	49.10	-
CRLO	215.1	-81.40	D	E58A	103.6	49.10	-
D56A	84.5	-81.90	D	F52A	240.8	49.10	-
VABQ	150.1	-82.10	D	G53A	220.3	49.10	+
PEMO	203.4	83.10	+	H55A	192.1	49.10	+ *
GAC	150.9	-83.30	D	DPQ	94.7	49.10	-
ALGO	228.4	49.10	- *	F51A	248.1	49.10	+
TRQ	118.3	49.10	-	H53A	212.7	49.10	+ *
F57A	132.2	49.10	+	E52A	247.1	49.10	D
E57A	107.8	49.10	+				

Table B.14: Polarity data used to determine the focal mechanism solutions for event 2014/03/30,
* means the data has been bandpass-filtered at 1 - 10 Hz.

Focal Mechanism Solution

Not including emergent polarity picks

Polarities/Errors: P 011/02

There are no amplitude ratio data

The minimum, increment and maximum B axis trend are 0.00 5.00 355.00

The limits for the B axis plunge are 0.00 5.00 90.00

The limits for the angle of the A axis are 0.00 5.00 85.00

Total number solutions: 137

#misfits:

Comments: undefined focal mechanism. It is likely thrust but the accurate orientation cannot be defined. I re-ran the Focmec and included the emergent data but I could not get solution.

Preferred solutions:

Nodal planes: cannot be determined

P-axis: the orientation is not well determined, but it seems the solutions are in SW and NE quadrants. Plunge cannot be well determined (probably shallow to moderate).

T-axis: the orientation is not well determined, but it seems the solutions are mainly dispersed in ESE and ENE and some in NW quadrants. Plunge is estimated approximately 45°-65° (near moderate).

B-axis: the orientation is not well determined, but it seems the solutions are mainly dispersed in NW and some in SE quadrants. Plunge cannot be well determined (probably moderate).

Figure B.58: Focal mechanism solutions for event 2014/03/30. Lower hemisphere projection, the format is the same as for Figure B.18.

2014/07/04

Latitude: 45.92N

Longitude: 74.86W

Depth: 19.48 km

Magnitude: 3.0 (M_N)

Origin Time: 22:55:57 (UT)

(Source: the GSC catalog, except depths which are from this study)

Polarity Data

Station	Azimuth (°)	Take-off Angle (°)	First Motion	Station	Azimuth (°)	Take-off Angle (°)	First Motion
F57A	136.5	-42.30	D	D56A	3.3	-81.10	D
ALFO	184.6	-59.70	D	E58A	673	-81.60	D
GAC	243.2	-70.40	D	D57A	31.0	-82.20	D
VABQ	267.8	-71.70	D	FRNY	140.4	-82.90	-
E56A	348.4	-74.40	C	F59A	92.3	49.10	+
E57A	45.0	-75.70	D	G55A	243.5	49.10	C
F58A	94.5	-76.40	+	PEMO	262.4	49.10	- *
G57A	186.6	78.10	D	E54A	288.2	49.10	C
G58A	144.0	-79.60	-	D54A	315.1	49.10	+
WBO	198.0	79.80	-	CRLO	274.5	49.10	+
GRQ	314.5	-79.80	C	D58A	48.6	49.10	D
E55A	302.6	-80.00	+	PLVO	241.2	49.10	C
F55A	265.4	-80.50	C *	G60A	114.2	49.10	D *
D55A	338.7	-81.50	-	F60A	87.8	49.10	+

Table B.15: Polarity data used to determine the focal mechanism solutions for event 2014/07/04,

* means the data has been bandpass-filtered at 1 - 10 Hz.

Focal Mechanism Solution

Not including emergent polarity picks

Polarities/Errors: P 017/01

There are no amplitude ratio data

The minimum, increment and maximum B axis trend are 0.00 2.00 355.00

The limits for the B axis plunge are 0.00 2.00 90.00

The limits for the angle of the A axis are 0.00 2.00 85.00

Dip	Strike	Rake	Pol: P
48.17	75.05	-21.20	1.0
46.21	75.81	-4.81	1.0
47.62	75.14	-13.15	1.0
48.11	75.40	-14.91	1.0
48.65	75.71	-16.62	1.0
49.25	76.06	-18.28	1.0
49.90	76.45	-19.89	1.0
51.37	74.51	-22.94	1.0
48.28	75.95	-5.38	1.0
48.50	76.29	-7.14	1.0
48.78	76.65	-8.89	1.0
49.12	77.04	-10.60	1.0
49.97	74.90	-13.94	1.0
50.48	75.38	-15.55	1.0
51.04	75.91	-17.12	1.0
52.32	74.07	-20.11	1.0
51.65	76.47	-18.64	1.0
53.03	74.72	-21.54	1.0
52.32	77.07	-20.11	1.0
53.79	75.42	-22.91	1.0
50.26	76.03	-5.01	1.0
50.18	77.33	-4.18	1.0
50.47	76.55	-6.66	1.0
51.04	74.54	-9.90	1.0
50.73	77.09	-8.29	1.0
51.41	75.13	-11.47	1.0
51.84	75.74	-13.02	1.0
52.84	73.95	-16.01	1.0
52.31	76.38	-14.54	1.0
53.42	74.66	-17.45	1.0
52.84	77.06	-16.01	1.0
54.04	75.41	-18.84	1.0
53.42	77.77	-17.45	1.0
52.17	75.67	-3.90	1.0
52.43	75.14	-6.21	1.0
52.24	77.66	-4.67	1.0

52.68	75.89	-7.73	1.0
53.32	74.19	-10.70	1.0
52.97	76.65	-9.23	1.0
53.71	75.00	-12.15	1.0
53.32	77.43	-10.70	1.0
54.16	75.83	-13.57	1.0
53.71	78.24	-12.15	1.0
54.65	76.69	-14.96	1.0
55.19	77.58	-16.31	1.0
55.78	78.51	-17.63	1.0
54.23	76.00	-4.34	1.0
54.16	77.23	-3.62	1.0
54.40	76.95	-5.77	1.0
54.63	77.90	-7.19	1.0
56.01	78.52	-12.65	1.0
56.15	78.91	-3.36	1.0

Total number solutions: 52 #misfits: 0

Preferred solutions: solutions are similar, so the closest to mean is used.

Plane 1:	Strike: 77°	Dip: 52°	Rake: -20°
Plane 2:	Strike: 180°	Dip: 74°	Rake: -141°
P-axis:	Trend: 45°	Plunge: 39°	
T-axis:	Trend: 304°	Plunge: 14°	
B-axis:	Trend: 198°	Plunge: 48°

P nodal planes

P, T and B axes

Figure B.59: Focal mechanism solutions for event 2014/07/04. Lower hemisphere projection, the format is the same as for Figure B.18.

2015/04/04

Latitude: 46.76N

Longitude: 75.80W

Depth: 18.46 km

Magnitude: 3.0 (M_N)

Origin Time: 17:23:00 (UT)

(Source: the GSC catalog, except depths which are from this study)

Polarity Data

Station	Azimuth (°)	Take-off Angle (°)	First Motion	Station	Azimuth (°)	Take-off Angle (°)	First Motion
GRQ	196.4	-42.90	D	ALGO	243.7	49.10	+
D55A	39.9	-64.30	D	E58A	101.5	49.10	+ *
E55A	210.9	-64.70	D	WBO	168.1	49.10	C
E56A	111.6	-73.60	C	PLVO	208.0	49.10	C
D56A	67.2	-77.80	D	D58A	79.3	49.10	C *
VABQ	171.2	-79.10	-	DPQ	91.0	49.10	+
GAC	168.0	-81.20	D	G54A	230.5	49.10	C *
F57A	140.5	-82.20	D *	VLDQ	317.9	49.10	-
CRLO	237.4	-82.80	D	G57A	160.8	49.10	D *
ORIO	171.2	-82.80	-	DELO	210.4	49.10	-
PEMO	223.6	49.10	D	F60A	105.1	49.10	C

Table B.16: Polarity data used to determine the focal mechanism solutions for event 2015/04/04,
* means the data has been bandpass-filtered at 1 - 10 Hz.

Focal Mechanism Solution

Not including emergent polarity picks

Polarities/Errors: P 015/02

There are no amplitude ratio data

The minimum, increment and maximum B axis trend are 0.00 5.00 355.00

The limits for the B axis plunge are 0.00 5.00 90.00

The limits for the angle of the A axis are 0.00 5.00 85.00

Dip	Strike	Rake	Pol: P	Dip	Strike	Rake	Pol: P
35.00	100.00	90.00	2.0	55.61	292.22	77.85	2.0
40.00	100.00	90.00	2.0	42.27	85.71	67.37	2.0
30.00	105.00	90.00	2.0	56.36	282.87	71.89	2.0
35.00	105.00	90.00	2.0	61.12	284.64	72.81	2.0
40.00	105.00	90.00	2.0	61.98	274.71	67.20	2.0
35.00	110.00	90.00	2.0	66.60	276.82	68.12	2.0
40.00	110.00	90.00	2.0	57.39	277.71	66.04	2.0
35.00	115.00	90.00	2.0	61.98	280.01	67.20	2.0
40.00	115.00	90.00	2.0	71.94	262.64	63.61	2.0
40.00	120.00	90.00	2.0	76.43	264.92	64.23	2.0
40.00	125.00	90.00	2.0	67.48	265.77	62.77	2.0
40.26	89.07	82.25	2.0	71.94	268.18	63.61	2.0
35.31	92.90	81.33	2.0	76.43	270.46	64.23	2.0
40.26	94.07	82.25	2.0	63.05	268.75	61.70	2.0
30.38	96.42	80.08	2.0	67.48	271.31	62.77	2.0
35.31	97.90	81.33	2.0	71.94	273.72	63.61	2.0
40.26	99.07	82.25	2.0	58.68	271.52	60.35	2.0
35.31	102.90	81.33	2.0	63.05	274.29	61.70	2.0
40.26	104.07	82.25	2.0	67.48	276.85	62.77	2.0
40.26	109.07	82.25	2.0	58.68	277.05	60.35	2.0
40.26	114.07	82.25	2.0	63.05	279.83	61.70	2.0
50.18	280.82	83.48	2.0	85.67	247.17	59.91	2.0
55.15	281.51	83.90	2.0	81.35	250.45	59.62	2.0
60.13	282.12	84.23	2.0	77.05	253.66	59.13	2.0
50.18	285.82	83.48	2.0	81.35	256.25	59.62	2.0
55.15	286.51	83.90	2.0	68.53	253.97	57.50	2.0
60.13	287.12	84.23	2.0	72.77	256.78	58.43	2.0
50.18	290.82	83.48	2.0	77.05	259.47	59.13	2.0
55.15	291.51	83.90	2.0	64.34	256.80	56.31	2.0
50.18	295.82	83.48	2.0	68.53	259.78	57.50	2.0
50.18	300.82	83.48	2.0	72.77	262.59	58.43	2.0
41.03	84.65	74.66	2.0	64.34	262.61	56.31	2.0
36.22	87.48	72.91	2.0	68.53	265.59	57.50	2.0
41.03	89.72	74.66	2.0	85.91	247.30	54.90	2.0
36.22	92.55	72.91	2.0	73.73	244.48	53.31	2.0
41.03	94.79	74.66	2.0	77.76	247.53	54.06	2.0

41.03	99.86	74.66	2.0	81.82	250.50	54.59	2.0
55.61	282.08	77.85	2.0	73.73	250.58	53.31	2.0
60.50	283.29	78.49	2.0	77.76	253.64	54.06	2.0
50.73	285.79	77.04	2.0	69.75	253.50	52.31	2.0
55.61	287.15	77.85	2.0	73.73	256.68	53.31	2.0
60.50	288.36	78.49	2.0	69.75	259.60	52.31	2.0
50.73	290.86	77.04	2.0	78.56	245.50	49.02	2.0

Total number solutions: 86

#misfits: 0

Comments:

Preferred solutions: solutions are similar, so the closest to mean is used.

Plane 1:	Strike: 274°	Dip: 63°	Rake: 62°
Plane 2:	Strike: 144°	Dip: 38°	Rake: 133°
P-axis:	Trend: 24°	Plunge: 14°	
T-axis:	Trend: 140°	Plunge: 61°	
B-axis:	Trend: 288°	Plunge: 25°	

Figure B.60

Figure B.61

Figure B.62

Figure B.63

Figure B.64

Figure B.65

Figure B.66

Figure B.67

Figure B.68

Figure B.69

Figure B.70

Figure B.71 **Figure B.72**

Figure B.73 **Figure B.74**

Figure B.75

Figure B.76

Figure B.77 **Figure B.78**

Figure B.79

Figure B.80

Figure B.81

Figures B.60 to B.81: Seismograms from which polarity data were read (event 2015/04/04). X- axis represents time (seconds) measured from origin time and Y- axis shows amplitude in digital counts.

Figure B.82: Focal mechanism solutions for event 2015/04/04. Lower hemisphere projection, the format is the same as for Figure B.18.

2015/04/20

Latitude: 46.77N

Longitude: 73.29W

Depth: 14.79 km

Magnitude: 3.8 (M_N)

Origin Time: 10:13:43 (UT)

(Source: the GSC catalog, except depths which are from this study)

Polarity Data

Station	Azimuth (°)	Take-off Angle (°)	First Motion	Station	Azimuth (°)	Take-off Angle (°)	First Motion
DPQ	103.2	-69.90	D	D55A	280.5	49.10	+
E58A	178.6	-71.30	+	ALFO	224.8	49.10	D
D58A	40.1	-72.90	- *	MOQ	153.2	49.10	C
STUQ	163.6	-74.60	+	G58A	198.5	49.10	D
E59A	117.5	-77.70	C	G60A	157.8	49.10	+
BECQ	126.6	-79.20	C	VABQ	242.7	49.10	-
LATQ	29.2	-79.40	D	GAC	235.8	49.10	D
F59A	158.7	-82.30	C	E55A	261.8	49.10	+ *
F58A	202.2	-82.20	C	ORIO	230.4	49.10	D
D59A	75.8	-82.60	+	G57A	216.1	49.10	D
TRQ	238.3	-82.60	D *	OTT	231.8	49.10	+
D56A	286.3	-82.70	-	WBO	218.9	49.10	-
F60A	130.1	-83.80	C	LONY	203.3	49.10	+
E56A	260.2	-83.80	-	DMCQ	20.1	49.10	-
MNTQ	190.5	-84.10	-	CRLO	257.1	49.10	D
F57A	226.1	49.10	D	PEMO	249.8	49.10	-
QCQ	88.7	-84.50	-	PLVO	238.2	49.10	+

Table B.17: Polarity data used to determine the focal mechanism solutions for event 2015/04/20,

* means the data has been bandpass-filtered at 1 - 10 Hz.

Focal Mechanism Solution

Not including emergent polarity picks

Polarities/Errors: P 016/00 There are no amplitude ratio data

The minimum, increment and maximum B axis trend are 0.00 5.00 355.00

The limits for the B axis plunge are 0.00 5.00 90.00

The limits for the angle of the A axis are 0.00 5.00 85.00

Dip	Strike	Rake	Pol: P	Dip	Strike	Rake	Pol: P
24.81	258.39	-35.42	0.0	46.03	279.86	-26.73	0.0
27.99	254.98	-43.22	0.0	54.07	269.82	-37.45	0.0
24.81	263.69	-35.42	0.0	51.13	274.92	-34.36	0.0
31.61	253.32	-49.26	0.0	48.44	280.43	-30.79	0.0
27.99	260.28	-43.22	0.0	57.20	271.64	-40.12	0.0
35.53	253.00	-53.95	0.0	54.07	276.36	-37.45	0.0
31.61	258.61	-49.26	0.0	60.50	273.80	-42.39	0.0
28.90	265.32	-29.03	0.0	57.20	278.19	-40.12	0.0
34.78	255.42	-42.19	0.0	63.94	276.23	-44.31	0.0
31.61	262.49	-36.26	0.0	60.50	280.34	-42.39	0.0
28.90	270.86	-29.03	0.0	67.48	278.91	-45.90	0.0
34.78	260.96	-42.19	0.0	63.94	282.78	-44.31	0.0
31.61	268.03	-36.26	0.0	71.11	281.78	-47.21	0.0
38.29	260.51	-47.00	0.0	67.48	285.45	-45.90	0.0
34.78	266.49	-42.19	0.0	71.11	288.32	-47.21	0.0
42.06	260.96	-50.89	0.0	74.81	291.35	-48.24	0.0
33.23	270.85	-24.15	0.0	46.92	284.54	-14.51	0.0
38.29	261.84	-36.20	0.0	52.24	273.12	-26.57	0.0
35.53	268.79	-30.64	0.0	50.14	278.95	-22.91	0.0
33.23	276.65	-24.15	0.0	54.60	274.69	-29.84	0.0
41.41	261.54	-40.89	0.0	52.24	280.18	-26.57	0.0
38.29	267.64	-36.20	0.0	50.14	286.01	-22.91	0.0
35.53	274.59	-30.64	0.0	60.00	271.73	-35.26	0.0
44.81	261.98	-44.81	0.0	54.60	281.75	-29.84	0.0
38.29	273.45	-36.20	0.0	62.97	274.21	-37.45	0.0
44.81	267.79	-44.81	0.0	60.00	278.79	-35.26	0.0
48.44	268.85	-48.07	0.0	57.20	283.65	-32.73	0.0
52.24	270.44	-50.77	0.0	62.97	281.27	-37.45	0.0
60.22	274.78	-54.82	0.0	60.00	285.85	-35.26	0.0
37.70	275.47	-20.29	0.0	69.30	279.85	-40.89	0.0
42.06	267.50	-31.11	0.0	66.07	283.99	-39.32	0.0
39.67	274.21	-26.03	0.0	72.61	282.95	-42.19	0.0
44.81	267.52	-35.53	0.0	69.30	286.91	-40.89	0.0
42.06	273.60	-31.11	0.0	76.00	286.20	-43.22	0.0
47.85	268.14	-39.32	0.0	72.61	290.01	-42.19	0.0
44.81	273.63	-35.53	0.0	79.45	289.55	-44.01	0.0
51.13	269.27	-42.55	0.0	76.00	293.26	-43.22	0.0
47.85	274.24	-39.32	0.0	52.84	283.72	-16.01	0.0

54.60	270.85	-45.28	0.0
51.13	275.37	-42.55	0.0
58.23	272.82	-47.57	0.0
61.98	275.10	-49.48	0.0
65.82	277.64	-51.04	0.0
42.27	280.10	-17.14	0.0
43.96	279.75	-22.18	0.0
51.13	268.37	-34.36	0.0
48.44	273.89	-30.79	0.0

56.17	279.95	-22.76	0.0
54.37	285.63	-19.53	0.0
60.50	277.18	-28.34	0.0
58.23	282.35	-25.70	0.0
56.17	287.78	-22.76	0.0
65.60	275.34	-32.73	0.0
62.97	280.06	-30.68	0.0
60.50	285.00	-28.34	0.0

Total number solutions: 93 #misfits: 0 Preferred solutions: solutions are similar, so the closest to mean is used.

Plane 1: Strike: 285° Dip: 48° Rake: -19°
 Plane 2: Strike: 28° Dip: 76° Rake: -137°
 P-axis: Trend: 256° Plunge: 40°
 T-axis: Trend: 151° Plunge: 17°
 B-axis: Trend: 42° Plunge: 45°

P nodal planes

P, T and B axes

Figure B.83: Focal mechanism solutions for event 2015/04/20. Lower hemisphere projection, the format is the same as for Figure B.18.

2015/05/02

Latitude: 46.83N
 Longitude: 78.93W
 Depth: 15.00 km
 Magnitude: 3.3 (M_N)
 Origin Time: 08:34:25 (UT)
 (Source: the GSC catalog)

Polarity Data

Station	Azimuth (°)	Take-off Angle (°)	First Motion	Station	Azimuth (°)	Take-off Angle (°)	First Motion
ALGO	144.9	-82.8	C	CRLO	126.0	-84.2	C
VLDQ	30.0	49.1	D	SUNO	264.3	49.1	D
KILO	342.5	49.1	C *	SADO	184.1	49.1	+
GAC	114.0	49.1	C	TRQ	99.9	49.1	-
DPQ	89.8	49.1	+	D55A	84.3	49.1	C *
D56A	84.2	49.1	-	E56A	94.8	49.1	- *
G54A	157.5	49.1	- *	H53A	173.7	49.1	- *
E57A	95.6	49.1	+ *	H57A	132.5	49.1	- *

Table B.18: Polarity data used to determine the focal mechanism solutions for event 2015/05/02,
 * means the data has been bandpass-filtered at 1 - 10 Hz.

Focal Mechanism Solution

***Including emergent polarity picks

Polarities/Errors: P 016/04 There are no amplitude ratio data

The minimum, increment and maximum B axis trend are 0.00 5.00 355.00

The limits for the B axis plunge are 0.00 5.00 90.00

The limits for the angle of the A axis are 0.00 5.00 85.00

Dip	Strike	Rake	Pol: P
50.73	223.78	-77.04	4.0
50.73	228.85	-77.04	4.0
41.03	90.28	-74.66	4.0
51.62	223.11	-70.72	4.0
48.36	220.06	-62.76	4.0
48.36	214.76	-62.76	4.0
52.84	227.78	-64.59	4.0
52.84	233.07	-64.59	4.0

50.14	219.53	-56.60	4.0
54.37	227.22	-58.67	4.0
54.37	232.76	-58.67	4.0
58.68	240.79	-60.35	4.0
42.06	100.34	-50.89	4.0
42.06	105.88	-50.89	4.0
52.24	223.98	-50.77	4.0
56.17	231.79	-53.00	4.0
58.23	236.21	-47.57	4.0
82.36	284.65	-49.57	4.0
82.36	111.35	49.57	4.0

Total number solutions: 19 solutions

Comments: undefined focal mechanism.

Nodal planes: cannot be determined

P-axis: the solutions are in SE quadrant. Plunge approximately 45° - 90° (moderate to vertical).

T-axis: the solutions are in NW quadrant. Plunge is estimated mainly horizontal.

B-axis: the solutions are mainly scattered in NE and some SE and SW quadrants. Plunge is approximately 15° - 40° .

P nodal planes

P, T and B axes

Figure B.84: Focal mechanism solutions for event 2015/05/02. Lower hemisphere projection, the format is the same as for Figure B.18.

2015/07/07

Latitude: 46.31N

Longitude: 75.08W

Depth: 20.00 km

Magnitude: 3.1 (M_N)

Origin Time: 09:46:30 (UT)

(Source: the GSC catalog)

Polarity Data

Station	Azimuth (°)	Take-off Angle (°)	First Motion	Station	Azimuth (°)	Take-off Angle (°)	First Motion
ALGO	261.4	-85.1	-	CRLO	261.2	49.10	D
DPQ	76.0	49.1	C	EEO	278.3	49.1	+
GAC	205.0	-74.9	D	GRQ	299.2	-73.8	C
MNTQ	128.0	-82.1	-	MOQ	115.8	49.1	-
ORIO	199.7	-78.8	C	OTT	206.3	-80.0	+
WBO	186.2	-82.2	D	D58A	61.6	49.1	-
E58A	86.4	-81.8	+ *	E60A	87.3	49.1	+ *
F58A	116.3	-79.8	+ *	F59A	105.2	49.1	- *
F60A	97.8	49.1	+ *	G57A	176.9	-81.6	D *
G58A	148.0	-82.5	D *	H57A	186.9	49.1	+ *
H58A	161.2	49.1	- *	H60A	103.0	49.1	- *
H59A	149.2	49.1	+ *				

Table B.19: Polarity data used to determine the focal mechanism solutions for event 2015/07/07,

* means the data has been bandpass-filtered at 1 - 10 Hz.

Focal Mechanism Solution

Not including emergent polarity picks

Polarities/Errors: P 008/00 There are no amplitude ratio data

The minimum, increment and maximum B axis trend are 0.00 5.00 355.00

The limits for the B axis plunge are 0.00 5.00 90.00

The limits for the angle of the A axis are 0.00 5.00 85.00

Dip	Strike	Rake	Pol: P
21.09	346.85	44.01	0.0
20.59	347.88	13.47	0.0
20.00	344.12	0.00	0.0

Total number solutions: 3

#misfits: 0

Preferred solution:

Plane 1:	Strike: 347°	Dip: 21°	Rake: 44°
Plane 2:	Strike: 215°	Dip: 76°	Rake: 105°
P-axis:	Trend: 292°	Plunge: 29°	
T-axis:	Trend: 145°	Plunge: 57°	
B-axis:	Trend: 31°	Plunge: 15°	

Figure B.85

Figure B.86

Figure B.87

Figure B.88

Figure B.89

Figure B.90

Figure B.91

Figure B.92

Figure B.93

Figure B.94

Figure B.95

Figure B.96

Figure B.97

Figure B.98

Figure B.99

Figure B.100 **Figure B.101**

Figure B.102

Figure B.103

Figure B.104

Figure B.105

Figure B.106 **Figure B.107**

Figures B.85 to B.107: Seismograms from which polarity data were read (event 2015/07/07). X- axis represents time (seconds) measured from origin time and Y- axis shows amplitude in digital counts.

Figure B.108: Focal mechanism solutions for event 2015/07/07. Lower hemisphere projection, the format is the same as for Figure B.18.

2015/07/15

Latitude: 45.47N

Longitude: 74.54W

Depth: 16.50 km

Magnitude: 3.9 (M_N)

Origin Time: 22:00:18 (UT)

(Source: the GSC catalog, except depths which are from this study)

Polarity Data

Station	Azimuth (°)	Take-off Angle (°)	First Motion	Station	Azimuth (°)	Take-off Angle (°)	First Motion
ALFO	302.6	-62.00	C	PLVO	257.1	49.10	-
MNTQ	87.8	-77.20	D	KGNO	228.5	49.10	+
ORIO	268.1	-77.60	D	PEMO	277.0	49.10	D
GAC	289.4	-77.80	D	D58A	35.0	49.10	D *
WBO	227.3	-78.00	D	CRLO	286.8	49.10	C
VABQ	300.3	-80.10	D	PECO	229.3	49.10	C
LONY	181.6	-80.20	D *	DELO	247.3	49.10	C
STUQ	50.5	-83.50	D	D59A	50.0	49.10	+ *
GRQ	321.5	-84.20	- *	BANO	260.3	49.10	+ *
MOQ	95.1	49.10	- *	EEO	291.9	49.10	+ *
DPQ	45.1	49.10	D	SADO	259.3	49.10	+ *
E59A	54.1	49.10	+ *				

Table B.20: Polarity data used to determine the focal mechanism solutions for event 2015/07/15,

* means the data has been bandpass-filtered at 1 - 10 Hz.

Focal Mechanism Solution

Not including emergent polarity picks

Polarities/Errors: P 014/00

There are no amplitude ratio data

The minimum, increment and maximum B axis trend are 0.00 2.00 355.00

The limits for the B axis plunge are 0.00 2.00 90.00

The limits for the angle of the A axis are 0.00 2.00 85.00

Dip	Strike	Rake	Pol: P	Dip	Strike	Rake	Pol: P
51.41	326.95	71.97	0.0	56.98	322.42	63.46	0.0
54.16	322.43	67.59	0.0	57.52	309.87	61.17	0.0
54.16	324.53	67.59	0.0	57.52	312.06	61.17	0.0
54.65	316.54	65.21	0.0	59.83	307.06	59.53	0.0
54.65	318.66	65.21	0.0	59.83	309.29	59.53	0.0
54.65	320.79	65.21	0.0	59.83	311.52	59.53	0.0
56.98	313.82	63.46	0.0	62.10	306.76	57.91	0.0
56.98	315.97	63.46	0.0	62.10	309.02	57.91	0.0
56.98	318.12	63.46	0.0	62.10	311.28	57.91	0.0
56.98	320.27	63.46	0.0	64.34	306.35	56.31	0.0
64.34	308.65	56.31	0.0				

Total number solutions: 21 #misfits: 0

Preferred solution: solutions are similar, so the closest to mean is used.

Plane 1: Strike: 317° Dip: 55° Rake: 65°

Plane 2: Strike: 175° Dip: 42° Rake: 121°

P-axis: Trend: 64° Plunge: 7°

T-axis: Trend: 171° Plunge: 69°

B-axis: Trend: 331° Plunge: 20°

P nodal planes

P, T and B axes

Figure B.109: Focal mechanism solutions for event 2015/07/15. Lower hemisphere projection, the format is the same as for Figure B.18.

2015/07/26

Latitude: 46.66N

Longitude: 75.61W

Depth: 18.00 km

Magnitude: 3.0 (M_N)

Origin Time: 22:36:13 (UT)

(Source: the GSC catalog)

Polarity Data

Station	Azimuth (°)	Take-off Angle (°)	First Motion	Station	Azimuth (°)	Take-off Angle (°)	First Motion
ALGO	248.3	49.1	+ *	DPQ	88.3	49.1	D
GAC	174.3	-80.4	D	GRQ	253.5	-47.4	D
ORIO	176.5	-82.4	+	OTT	183.3	-82.7	+ *
VABQ	179.6	-77.8	D	H57A	175.8	49.1	C *
H58A	155.3	49.1	- *	H59A	145.5	49.1	+ *

Table B.21: Polarity data used to determine the focal mechanism solutions for event 2015/07/26,

* means the data has been bandpass-filtered at 1 - 10 Hz.

Focal Mechanism Solution

***Including emergent polarity picks

Polarities/Errors: P 010/01 There are no amplitude ratio data

The minimum, increment and maximum B axis trend are 0.00 5.00 355.00

The limits for the B axis plunge are 0.00 5.00 90.00

The limits for the angle of the A axis are 0.00 5.00 85.00

Dip	Strike	Rake	Pol: P	Dip	Strike	Rake	Pol: P
10.00	285.00	-90.00	1.0	85.08	348.99	79.96	1.0
10.00	290.00	-90.00	1.0	90.00	354.93	80.00	1.0
10.00	295.00	-90.00	1.0	75.23	352.27	79.65	1.0
10.00	300.00	-90.00	1.0	80.15	353.18	79.85	1.0
10.00	305.00	-90.00	1.0	85.08	354.06	79.96	1.0
15.00	325.00	-90.00	1.0	17.96	323.16	-32.95	1.0
20.00	330.00	-90.00	1.0	17.96	328.31	-32.95	1.0
11.17	296.30	-63.26	1.0	21.09	332.01	-44.01	1.0
11.17	301.30	-63.26	1.0	24.81	333.70	-51.92	1.0
11.17	306.30	-63.26	1.0	24.81	338.85	-51.92	1.0
11.17	311.30	-63.26	1.0	28.90	337.60	-57.62	1.0
15.79	318.02	-71.32	1.0	33.23	343.00	-61.81	1.0
15.79	323.02	-71.32	1.0	37.70	344.29	-64.96	1.0
15.79	328.02	-71.32	1.0	90.00	303.43	75.00	1.0

20.59	333.47	-75.65	1.0	22.27	332.73	-25.51	1.0
25.46	335.59	-78.30	1.0	24.81	337.81	-35.42	1.0
80.04	150.88	-84.92	1.0	27.99	339.69	-43.22	1.0
80.04	155.88	-84.92	1.0	31.61	343.32	-49.26	1.0
80.04	160.88	-84.92	1.0	26.81	335.97	-20.42	1.0
75.06	161.34	-84.82	1.0	28.90	337.32	-29.03	1.0
14.11	315.83	-44.56	1.0	31.61	340.03	-36.26	1.0
14.11	320.90	-44.56	1.0	34.78	344.03	-42.19	1.0
17.96	324.50	-55.73	1.0	44.81	347.70	44.81	1.0
17.96	329.57	-55.73	1.0	31.47	343.48	-16.47	1.0
22.27	332.27	-62.73	1.0	33.23	340.52	-24.15	1.0
26.81	337.33	-67.35	1.0	35.53	344.27	-30.64	1.0
31.47	343.78	-70.57	1.0	51.13	350.05	42.55	1.0
80.15	80.35	-79.85	1.0	36.22	344.44	-13.93	1.0
85.08	109.88	-79.96	1.0	51.13	350.18	34.36	1.0
85.08	114.95	-79.96	1.0	41.03	346.30	-11.69	1.0
90.00	324.51	80.00	1.0	45.86	347.53	9.85	1.0
85.08	343.92	79.96	1.0	45.22	347.64	4.98	1.0
80.15	348.11	79.85	1.0	52.84	350.20	16.01	1.0

Total number solutions: 66 solutions

Comments: undefined focal mechanism. It is thrust/strike-slip but the accurate orientation cannot be defined.

Preferred solutions: Nodal planes: cannot be determined

P-axis: solutions are mainly dispersed in NE, some solutions in NW quadrant. Plunge is moderate.

T-axis: solutions are mainly in SW. Plunge is not well determined, near moderate.

B-axis: solutions in NW and SE and some in NE quadrants. Plunge approximately horizontal to moderate (0° - 40°)

Figure B.110: Focal mechanism solutions for event 2015/07/26. Lower hemisphere projection, the format is the same as for Figure B.18.

2015/07/27

Latitude: 46.56N

Longitude: 75.28W

Depth: 18.00 km

Magnitude: 3.1 (M_N)

Origin Time: 20:26:26 (UT)

(Source: the GSC catalog)

Polarity Data

Station	Azimuth (°)	Take-off Angle (°)	First Motion	Station	Azimuth (°)	Take-off Angle (°)	First Motion
GRQ	276.3	-68.1	D	CRLO	250.9	49.1	D
DPQ	85.2	49.1	C	GAC	189.2	-79.5	D *
KB1O	208.5	-83.0	+	ORIO	188.3	-81.8	-
VABQ	199.2	-76.9	D	WBO	179.9	49.1	D
H57A	182.2	49.1	C *	H58A	159.8	49.1	+ *
H59A	149.3	49.1	+ *	H60A	137.0	49.1	+ *

Table B.22: Polarity data used to determine the focal mechanism solutions for event 2015/07/27,

* means the data has been bandpass-filtered at 1 - 10 Hz.

Focal Mechanism Solution

***Including emergent polarity picks

Polarities/Errors: P 012/01

There are no amplitude ratio data

The minimum, increment and maximum B axis trend are 0.00 5.00 355.00

The limits for the B axis plunge are 0.00 5.00 90.00

The limits for the angle of the A axis are 0.00 5.00 85.00

Dip	Strike	Rake	Pol: P	Dip	Strike	Rake	Pol: P
25.00	30.00	90.00	1.0	33.23	1.57	61.81	1.0
30.00	30.00	90.00	1.0	24.81	355.44	51.92	1.0
35.00	30.00	90.00	1.0	28.90	1.83	57.62	1.0
25.46	14.41	78.30	1.0	33.23	6.71	61.81	1.0
30.38	16.42	80.08	1.0	24.81	0.58	51.92	1.0
60.13	207.12	84.23	1.0	28.90	6.97	57.62	1.0
55.15	211.51	83.92	1.0	24.81	5.73	51.92	1.0
60.13	212.12	84.23	1.0	28.90	12.11	57.62	1.0
22.27	4.92	62.73	1.0	24.81	10.87	51.92	1.0

26.81	10.00	67.35	1.0	56.36	210.87	71.89	1.0
31.47	13.68	70.57	1.0	35.53	1.12	53.95	1.0
22.27	9.99	62.73	1.0	27.99	353.84	43.22	1.0
60.50	207.23	78.49	1.0	31.61	0.80	49.26	1.0
55.61	211.10	77.85	1.0	24.81	350.43	35.42	1.0
60.50	212.30	78.49	1.0	27.99	359.13	43.22	1.0
24.81	350.30	51.92	1.0	24.81	355.72	35.42	1.0
28.90	356.68	57.62	1.0	24.81	1.02	35.42	1.0
22.27	355.51	25.51	1.0				

Total number solutions: 35

Preferred solution: solutions are similar, so the closest to mean is used.

Plane 1:	Strike: 212°	Dip: 61°	Rake: 78°
Plane 2:	Strike: 55°	Dip: 31°	Rake: 109°
P-axis:	Trend: 310°	Plunge: 15°	
T-axis:	Trend: 95°	Plunge: 72°	
B-axis:	Trend: 218°	Plunge: 10°

Figure B.111: Focal mechanism solutions for event 2015/07/27. Lower hemisphere projection, the format is the same as for Figure B.18.

2015/08/05

Latitude: 45.89N

Longitude: 75.59W

Depth: 15.00 km

Magnitude: 3.4 (M_N)

Origin Time: 07:37:51 (UT)

(Source: the GSC catalog)

Polarity Data

Station	Azimuth (°)	Take-off Angle (°)	First Motion	Station	Azimuth (°)	Take-off Angle (°)	First Motion
GAC	157.8	-56.6	D	ORIO	172.9	-73.1	D
KB1O	220.0	-78.2	D	ALGO	272.9	49.1	D
A11	68.1	49.1	+	A61	62.5	49.1	+
CRLO	227.3	-83.9	D	DPQ	67.0	49.1	D
GRQ	345.3	-79.6	C	OTT	190.2	-75.1	D
SADO	247.1	49.1	+	F62A	87.9	49.1	+ *
H23K	324.6	49.1	+ *	H24K	324.4	49.1	+ *
H57A	174.3	49.1	D *	H58A	145.5	49.1	D *
H59A	132.3	49.1	D *	H60A	122.2	49.1	-
HARP	319.1	49.1	+ *				

Table B.23: Polarity data used to determine the focal mechanism solutions for event 2015/08/05,
* means the data has been bandpass-filtered at 1 - 10 Hz.

Focal Mechanism Solution

Not including emergent polarity picks

Polarities/Errors: P 011/01

There are no amplitude ratio data

The minimum, increment and maximum B axis trend are 0.00 5.00 355.00

The limits for the B axis plunge are 0.00 5.00 90.00

The limits for the angle of the A axis are 0.00 5.00 85.00

Dip	Strike	Rake	Pol: P
21.09	33.72	-44.01	1.0
24.81	37.93	-35.42	1.0
27.99	37.93	-43.22	1.0
39.67	41.92	-57.60	1.0
31.61	40.96	-36.26	1.0
28.90	49.32	-29.03	1.0
34.78	39.42	-42.19	1.0
31.61	46.49	-36.26	1.0
34.78	44.96	-42.19	1.0
38.29	44.51	-47.00	1.0
35.53	48.14	-30.64	1.0
38.29	47.00	-36.20	1.0
38.29	52.80	-36.20	1.0
39.67	54.55	-26.03	1.0

Total number solutions: 14 #misfits: 0

Preferred solution: solutions are similar, so the closest to mean is used.

Plane 1: Strike: 44° Dip: 38° Rake: -47°
 Plane 2: Strike: 175° Dip: 63° Rake: -118°
 P-axis: Trend: 41° Plunge: 61°
 T-axis: Trend: 285° Plunge: 14°
 B-axis: Trend: 188° Plunge: 25°

Figure B.112: Focal mechanism solutions for event 2015/08/05. Lower hemisphere projection, the format is the same as for Figure B.18.

2015/08/17

Latitude: 45.91N

Longitude: 74.82W

Depth: 18.00 km

Magnitude: 3.1 (M_N)

Origin Time: 23:11:16 (UT)

(Source: the GSC catalog)

Polarity Data

Station	Azimuth (°)	Take-off Angle (°)	First Motion	Station	Azimuth (°)	Take-off Angle (°)	First Motion
GAC	245.5	-72.2	D	ALFO	188.6	-60.8	D
CRLO	274.9	49.1	C	DPQ	60.9	49.1	C
GRQ	314.3	-80.8	D	KB1O	241.9	-81.5	D
ORIO	226.4	-76.4	D	OTT	230.6	-78.8	-
VABQ	269.3	-73.5	D *	WBO	199.4	-80.5	C
H60A	131.4	49.1	+ *	I57A	196.9	49.1	C *
I59A	162.1	49.1	+ *	I60A	151.8	49.1	+

Table B.24: Polarity data used to determine the focal mechanism solutions for event 2015/08/17,

* means the data has been bandpass-filtered at 1 - 10 Hz.

Focal Mechanism Solution

Not including emergent polarity picks

Polarities/Errors: P 009/00

There are no amplitude ratio data

The minimum, increment and maximum B axis trend are 0.00 2.00 355.00

The limits for the B axis plunge are 0.00 2.00 90.00

The limits for the angle of the A axis are 0.00 2.00 85.00

Dip	Strike	Rake	Pol: P
47.47	10.25	62.35	0.0
47.24	8.54	56.36	0.0

Total number solutions: 2 #misfits: 0
Preferred solution: solutions are similar.

Plane 1:	Strike: 10°	Dip: 47°	Rake: 62°
Plane 2:	Strike: 228°	Dip: 49°	Rake: 117°
P-axis:	Trend: 299°	Plunge: 1°	
T-axis:	Trend: 207°	Plunge: 70°	
B-axis:	Trend: 30°	Plunge: 20°

P nodal planes

P, T and B axes

Figure B.113: Focal mechanism solutions for event 2015/08/17. Lower hemisphere projection, the format is the same as for Figure B.18.

2015/08/30

Latitude: 46.06N

Longitude: 75.62W

Depth: 18.00 km

Magnitude: 3.2 (M_N)

Origin Time: 20:27:39 (UT)

(Source: the GSC catalog)

Polarity Data

Station	Azimuth (°)	Take-off Angle (°)	First Motion	Station	Azimuth (°)	Take-off Angle (°)	First Motion
CRLO	269.3	-82.5	C	EEO	284.8	-49.1	+
GAC	164.3	-66.7	C	GRQ	343.3	-74.0	D
OTT	185.6	-76.5	- *	SADO	243.7	49.1	-
K22A	272.4	49.1	D *	G64A	202.3	49.1	+ *
E62A	195.0	49.1	- *	H23K	220.5	49.1	+ *

Table B.25: Polarity data used to determine the focal mechanism solutions for event 2015/08/30,

* means the data has been bandpass-filtered at 1 - 10 Hz.

Focal Mechanism Solution

***Including emergent polarity picks

Polarities/Errors: P 007/00

There are no amplitude ratio data

The minimum, increment and maximum B axis trend are 0.00 5.00 355.00

The limits for the B axis plunge are 0.00 5.00 90.00

The limits for the angle of the A axis are 0.00 5.00 85.00

Total number solutions: 186

Comments: undefined focal mechanism. It is likely thrust/strike-slip but the accurate orientation cannot be defined.

Preferred solutions:

Nodal planes: cannot be determined

P-axis: solutions are dispersed in SW quadrant. Plunge is approximately 35° - 90° (moderate to vertical).

T-axis: solutions are mainly dispersed in NE and some solutions in ESE quadrants. Plunge is approximately 10° - 45° (shallow to moderate).

B-axis: solutions are dispersed in NW, SE and WNE quadrants. Plunge is approximately 0° - 50° (shallow to moderate).

Figure B.114: Focal mechanism solutions for event 2015/08/30. Lower hemisphere projection, the format is the same as for Figure B.18.

2015/09/09

Latitude: 45.76N

Longitude: 76.34W

Depth: 14.50 km

Magnitude: 3.7 (M_N)

Origin Time: 19:17:50 (UT)

(Source: the GSC catalog)

Polarity Data

Station	Azimuth (°)	Take-off Angle (°)	First Motion	Station	Azimuth (°)	Take-off Angle (°)	First Motion
KB1O	162.1	-71.3	D	GAC	95.4	-77.9	D
A11	68.6	49.1	+	ALGO	279.7	-83.8	D
EEO	295.8	49.1	D	GRQ	21.6	-81.8	D
KGNO	184.0	49.1	+ *	MNTQ	96.9	49.1	+
MOQ	97.5	49.1	-	ORIO	117.9	-78.9	+
OTT	129.8	-77.2	+ *	QCQ	72.1	49.1	- *
SADO	244.3	49.1	C	VABQ	74.5	-76.3	D
WBO	135.0	-83.1	- *	E62A	101.5	49.1	- *
H23K	259.4	49.1	+ *	F62A	237.0	49.1	- *

Table B.26: Polarity data used to determine the focal mechanism solutions for event 2015/09/09,

* means the data has been bandpass-filtered at 1 - 10 Hz.

Focal Mechanism Solution

Not including emergent polarity picks

Polarities/Errors: P 007/00

There are no amplitude ratio data

The minimum, increment and maximum B axis trend are 0.00 5.00 355.00

The limits for the B axis plunge are 0.00 5.00 90.00

The limits for the angle of the A axis are 0.00 5.00 85.00

Total number solutions: 264

Comments: undefined focal mechanism. It is likely thrust but the accurate orientation cannot be defined.

Preferred solutions:

Nodal planes: cannot be determined

P-axis: is not well determined, solutions are mainly dispersed in NW, SE and some in NE quadrants. Plunge is nearly horizontal in SE and NE, horizontal to moderate in NW quadrant.

T-axis: solutions are in ENE and ESE quadrants. Plunge is near vertical to moderate.

B-axis: is not well determined, solutions are mainly dispersed in SW, NE and some in NWN quadrants. Plunge is nearly horizontal in NE, shallow to moderate in SW and NWN quadrants.

Figure B.115: Focal mechanism solutions for event 2015/09/09. Lower hemisphere projection, the format is for same as the Figure B.18.

2015/10/08

Latitude: 47.15N

Longitude: 75.91W

Depth: 18.00 km

Magnitude: 3.2 (M_N)

Origin Time: 21:28:27 (UT)

(Source: the GSC catalog)

Polarity Data

Station	Azimuth (°)	Take-off Angle (°)	First Motion	Station	Azimuth (°)	Take-off Angle (°)	First Motion
ALGO	231.7	49.1	D	CRLO	222.8	49.1	+ *
EEO	257.9	49.1	C	GAC	168.2	49.1	+
GRQ	176.3	-74.1	+	KB1O	186.1	49.1	-
SUNO	264.2	49.1	-	TRQ	134.5	-83.1	C
VABQ	170.4	-82.7	D *	H17A	187.7	49.1	+ *
H23K	105.5	49.1	- *	HARP	283.6	49.1	+ *

Table B.27: Polarity data used to determine the focal mechanism solutions for event 2015/10/08,
* means the data has been bandpass-filtered at 1 - 10 Hz.

Focal Mechanism Solution

Not including emergent polarity picks

Polarities/Errors: P 004/00

There are no amplitude ratio data

The minimum, increment and maximum B axis trend are 0.00 5.00 355.00

The limits for the B axis plunge are 0.00 5.00 90.00

The limits for the angle of the A axis are 0.00 5.00 85.00

Total number solutions: more than 1000 solutions (1159 solutions)

Comments: undefined focal mechanism. It is likely thrust/strike-slip but the accurate orientation cannot be defined.

Preferred solutions:

Nodal planes: cannot be determined

P-axis: solutions are mainly in SW and some in NE quadrants. Plunge is not well determined in SW, shallow to moderate in NE.

T-axis: solutions are mainly in NW and some in SE quadrants. Plunge is not well determined in NW, shallow to moderate in SE.

B-axis: is not well determined, solutions are nearly in every azimuth. Plunge is not well determined (shallow to moderate).

Figure B.116: Focal mechanism solutions for event 2015/10/08. Lower hemisphere projection, the format is the same as for Figure B.18.

2015/10/20-A

Latitude: 45.73N

Longitude: 77.12W

Depth: 15.00 km

Magnitude: 3.7 (M_N)

Origin Time: 23:34:52 (UT)

(Source: the GSC catalog)

Polarity Data

Station	Azimuth (°)	Take-off Angle (°)	First Motion	Station	Azimuth (°)	Take-off Angle (°)	First Motion
ALGO	289.1	-78.9	D	EEO	304.5	49.1	C
GAC	90.9	-83.3	D	GAX1	90.9	-83.3	D *
GAX2	90.9	-83.3	- *	GAX3	90.9	-83.3	D *
GRQ	44.6	-83.8	D	KGNO	163.3	49.1	D
OTT	108.5	-82.6	+	SADO	236.7	49.1	D
WBO	118.7	49.1	D	HARP	205.0	49.1	+ *
H17A	105.6	46.1	+ *	H21K	185.3	49.1	- *

Table B.28: Polarity data used to determine the focal mechanism solutions for event 2015/10/20-A, * means the data has been bandpass-filtered at 1 - 10 Hz.

Focal Mechanism Solution

Not including emergent polarity picks

Polarities/Errors: P 009/00

There are no amplitude ratio data

The minimum, increment and maximum B axis trend are 0.00 5.00 355.00

The limits for the B axis plunge are 0.00 5.00 90.00

The limits for the angle of the A axis are 0.00 5.00 85.00

Total number solutions: 495

Comments: undefined focal mechanism. It is likely thrust but the accurate orientation cannot be defined.

Preferred solutions:

Nodal planes: cannot be determined

P-axis: solutions are mainly in ESE and some in NE quadrants. Plunge is approximately 0° - 30° (horizontal to moderate).

T-axis: solutions are in NNW and some in NNE quadrants. Plunge is nearly moderate.

B-axis: is not well determined, solutions are mainly dispersed in SW, SE and some in NW quadrants. Plunge is approximately 10° - 45° (shallow to moderate).

Figure B.117: Focal mechanism solutions for event 2015/10/20-A. Lower hemisphere projection, the format is the same as for Figure B.18.

2015/10/20-B

Latitude: 45.73N

Longitude: 77.14W

Depth: 18.00 km

Magnitude: 3.1 (M_N)

Origin Time: 23:36:56 (UT)

(Source: the GSC catalog)

Polarity Data

Station	Azimuth (°)	Take-off Angle (°)	First Motion	Station	Azimuth (°)	Take-off Angle (°)	First Motion
PEMO	236.4	-29.1	D	ALGO	290.0	-76.5	-
GAC	90.6	-82.1	-	GAX1	90.6	-82.1	- *
GRQ	44.8	-82.6	+	VABQ	80.0	-81.5	+
WBO	118.3	49.1	-	H24A	100.5	49.1	- *
H17A	225.0	49.1	+ *				

Table B.29: Polarity data used to determine the focal mechanism solutions for event 2015/10/20-B, * means the data has been bandpass-filtered at 1 - 10 Hz.

Focal Mechanism Solution

***Including emergent polarity picks

Polarities/Errors: P 007/00

There are no amplitude ratio data

The minimum, increment and maximum B axis trend are 0.00 5.00 355.00

The limits for the B axis plunge are 0.00 5.00 90.00

The limits for the angle of the A axis are 0.00 5.00 85.00

Total number solutions: 518

Comments: undefined focal mechanism. Preferred solutions:

Nodal planes: cannot be determined

P-axis: solutions are mainly in SE and some in ENE quadrants. Plunge is not well determined, shallow to moderate.

T-axis: solutions are mainly in SW and some in NNE quadrants. Plunge is shallow to moderate.

B-axis: solutions are mainly dispersed in NW and some in ESE quadrants. Plunge is shallow to moderate in NW, near horizontal in ESE.

Figure B.118: Focal mechanism solutions for event 2015/10/20-B. Lower hemisphere projection, the format is the same as for Figure B.18.

2015/11/28

Latitude: 44.98N

Longitude: 74.71W

Depth: 12.00 km

Magnitude: 3.7 (M_N)

Origin Time: 05:16:53 (UT)

(Source: the GSC catalog)

Polarity Data

Station	Azimuth (°)	Take-off Angle (°)	First Motion	Station	Azimuth (°)	Take-off Angle (°)	First Motion
ALFO	349.5	-80.6	D	ALGO	293.6	49.1	+
CRLO	300.3	49.1	-	DPQ	37.9	49.1	C
EEO	300.1	49.1	+	GAC	323.4	-83.1	C
GAX1	323.4	-83.1	C *	GAX2	323.4	-83.1	C *
GAX3	323.4	-83.1	C *	KB1O	292.3	-84.5	+
KB2O	292.0	-84.4	+	KB3O	291.7	-84.3	C
KB4O	291.3	-84.4	C *	KB5O	292.5	-84.3	+
KB6O	292.1	-84.4	+	KGNO	239.8	-85.8	C *
MNTQ	55.9	-83.1	D	ORIO	310.0	-81.6	C
OTT	300.4	-82.5	C	TRQ	5.3	-85.0	D
VABQ	326.0	-84.5	C	WBO	272.6	-74.8	C
H17A	215.6	49.1	+ *	H24A	208.4	49.1	- *

Table B.30: Polarity data used to determine the focal mechanism solutions for event 2015/11/28,

* means the data has been bandpass-filtered at 1 - 10 Hz.

Focal Mechanism Solution

***Including emergent polarity picks

Polarities/Errors: P 022/01

There are no amplitude ratio data

The minimum, increment and maximum B axis trend are 0.00 5.00 355.00

The limits for the B axis plunge are 0.00 5.00 90.00

The limits for the angle of the A axis are 0.00 5.00 85.00

Total number solutions: 92

Comments: undefined focal mechanism. It is likely thrust/strike-slip but the accurate orientation cannot be defined.

Preferred solutions:

Nodal planes: cannot be determined

P-axis: solutions are dispersed in SW and some in SE quadrants. Plunge is nearly moderate.

T-axis: solutions are dispersed in NW and SE quadrants. Plunge is shallow to moderate, some nearly horizontal in NW and SE.

B-axis: solutions are mainly in NE, and some in NW quadrants. Plunge is shallow to moderate.

Figure B.119: Focal mechanism solutions for event 2015/11/28. Lower hemisphere projection, the format is the same as for Figure B.18.