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GEOLOGICAL SURVEY OF CANADA
OPEN FILE 8253

Procedures for seismic event type discrimination at the Canadian Hazards Information Service

Version 1.0

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Abstract

Within a catalogue of seismic events, it is necessary to distinguish natural tectonic earthquakes from seismic events due to human activity or other natural processes. This becomes very important when the data are incorporated into models of seismic hazard, since natural and anthropogenic events follow different recurrence and scaling laws. This document outlines a two-step procedure whereby first, a most likely event type is identified, and second, confirmation or refutation is sought. The procedure is intended to be compatible with current and past practices at the Canadian Hazards Information Service and the Geological Survey of Canada in assigning event types in the National Earthquake Database (NEDB). Furthermore, this document presents a new nomenclature and coding system for event types and their certainty, one that is compatible with QuakeML. Detailed classification criteria are given for all common event types; for rare event types, only definitions and examples are given.

Résumé

Dans un catalogue d'événements sismiques, il faut distinguer les séismes tectoniques naturels et les événements sismiques liés à l'activité humaine ou à d'autres processus naturels. Cela devient très important lorsque les données sont incorporées dans les modèles de l’aléa sismique, étant donné que les événements naturels et anthropiques suivent des lois différentes de récurrence et de proportionnalité. Ce document décrit une procédure en deux étapes par laquelle d'abord, un type d'événement le plus probable est identifié, et deuxièmement, une confirmation ou une réfutation est recherchée. La procédure est conçue pour être compatible avec les pratiques actuelles et passées du Service canadien d'information sur les risques et de la Commission géologique du Canada pour l'attribution des types d'événements dans la Base nationale de données sismologiques (BNDS). En outre, ce document présente un nouveau système de nomenclature et de codage pour les types d'événements et leur certitude, ce qui est compatible avec QuakeML. Des critères de classification détaillés sont fournis pour tous les types d'événements courants ; pour les types d'événements rares, des définitions et des exemples sont fournis.

Version History

Version	Date	Summary of Changes
1.0	2022-01-18	Initial version.

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Background

The Canadian Hazards Information Service (CHIS)[1], a division of Natural Resources Canada (NRCan), is the authoritative source for information about earthquakes in and near Canada. While the primary aim is to monitor and characterise earthquakes, seismic analysts must inevitably characterise other types of seismic events, including those related to industrial activity. The primary goal of this document is to describe how seismic events are categorized at CHIS.

A secondary goal is to guide the actions of CHIS Seismologists on Call (SOC) in the immediate aftermath of a "significant" seismic event in or near Canada. Significant in this context refers to events that are magnitude 4 or greater, felt by many people, or deemed noteworthy for other reasons. To achieve this end, the procedure must allow for a rapid initial assessment, which is subject to subsequent reassessment upon review of other types of data or confirmation by third parties.

The level of detail provided in this document is intended to be sufficient for a person experienced in seismic analysis to understand and implement. It is not intended to be a comprehensive and systematic procedure, and it is not a primer in the basics of seismology.

Note to the Reader: This document will be updated as procedures at CHIS evolve.

Seismologists' On-Call Response to Significant Seismic Events

The expectations of a SOC are defined by the "Standard Operating Procedures for Seismologists On Call" (CHIS; NRCan, 2021). The goal of that document is to ensure prompt, accurate and authoritative information relating to significant seismic events within or near Canada.

The SOC is responsible for coordinating the response in the immediate aftermath of a significant event, including:

1. Confirming the event's time, location and magnitude.
2. Assessing, objectively, the "nature of the event", with reference to seismological observations and literature as well as maps of tectonics, past seismic events and industrial activity, and similar materials when applicable.
3. Posting information to the EarthquakesCanada and SeismesCanada webpages (see Internet Sources), disseminating an Earthquake Report (to senior government managers, emergency response organisations and the news media), and ensuring that an accurate message has been posted to the Earthquakes Canada Twitter account.
4. Conveying an assessment of the event to government operations centres, the media and the public, including:
    a. Stating the event's location, magnitude and intensity details (where felt or damaging, if applicable) and, if appropriate, tsunami potential (with reference to the authoritative source, the Tsunami Warning Centres, see Internet Sources)
    b. Commenting on what is known seismologically (for example, expected felt area or types of damage, historical seismicity and tectonic context)
    c. If applicable, stating that "based on assessment criteria, the event is characteristic of / consistent with an earthquake / an explosion / an industry-related seismic event"

[1] CHIS was part of the Geological Survey of Canada until 2018, when it became an independent entity within the Lands and Minerals Sector.

   d. Conveying the uncertainty associated with any event type assessment. In particular, as long as the event's source type is uncertain (i.e. suspected rather than known), the SOC will:
      i. Avoid terms more specific than what is actually known, for example by preferring "industry-related seismic event" to either "fluid injection induced or triggered event" or "rock burst"
      ii. Make it clear that "further investigation is required"
5. Seeking confirmation with the relevant provincial regulator, when the event is suspected to be a fluid injection induced or triggered event.

Seismic Analysts' Categorisation of Seismic Events

Every effort is made to keep the Canadian National Earthquake Database (NEDB) as complete and as accurate as possible. This includes each event's type being appropriately assigned. The assignment of event type (a.k.a. "flagging" or "screening" of events) is crucial for (1) reasonable comparison of recent activity to historical activity, and (2) accurate seismic hazard assessment. As is standard practice, analysts use their knowledge of the region to help identify mining, quarry, and other blast sources, including: time of day, location, waveform characteristics and occasionally, advanced notification of planned activity.

Ideally, assignment of event type should be done as soon as the event has been located and prior to it being added to the NEDB or otherwise published. It is unlikely that there can be confirmation from industry or regulators of the nature of an anthropogenic event within this limited timeframe. As detailed below, in these cases, familiarity with industrial activity, assessment of events' characteristics and historical knowledge all come into play in the initial assessment of the most likely event type.

Seismic events are located primarily using data from the Canadian National Seismograph Network (CNSN), but seismic data from other networks (e.g. Pacific Northwest Seismic Network, Alaska Earthquake Information Center, Southern Ontario Seismic Network) are routinely incorporated.

Event Type Nomenclature

The NEDB "eq" database schema was developed over time in response to the needs at the Geological Survey of Canada (GSC), and later, CHIS. The schema (and associated NPF "pickfile" format) defines a free-form four-character "eqtype" field, which has historically been used to store a single uppercase character. These codes and their meanings are summarized in the first two columns of Table 1. Prior to this document, no detailed criteria for the assignment of these event types within the NEDB has been published.

When CHIS started characterising events using SeisComP in 2017, it was decided to start working towards adoption of the event types defined by the seismic data interchange format QuakeML 1.2 (Schorlemmer, Euchner, Kästli, & Saul, 2011), along with the lower-case two-letter coding and hierarchy of Storchak, et al. (2012). This choice satisfies the requirement that all existing event types be representable in the NEDB, while enabling the classification of types not previously supported. The proposed equivalents to historical NEDB eqtype codes are summarized in the third and fourth columns of Table 1.

Table 1: NEDB eqtype codes and their QuakeML equivalents. Rows are ordered (approximately) in descending order of frequency; counts and year ranges are given in the final column, up to the end of 2020. Note that NEDB eqtype "R" has different meaning in western and eastern Canada, and that some NEDB eqtype codes are very rare, or arguably not even event types. See Tables 2-3 of Appendix A for the full set of two-letter codes of Storchak, et al. (2012) and their QuakeML equivalents. See Table 6 in Appendix D for a proposal as to how the NEDB eqtype field can support both the historical single-letter code and the new two-letter codes.

NEDB eqtype	NEDB Mnemonic	QuakeML Equivalent	Two-letter Equivalent	Comment	NEDB Count: Years
L	earthquake, local	"*known earthquake*"	ke		121,322: 1568–2020
B	blast	"*known controlled explosion*" or sub-type	kg, kd, km		24,428: 1980–2020
P	possible blast	"*suspected controlled explosion*" or sub-type	sg, sd, sm		2,197: 1983–2020
R	rockburst earthquake, regional	"*known rock burst*" "*known earthquake*"	kr ke	east west	3,245: 1985–2020
U	unconfirmed rockburst	"*suspected rock burst*"	sr		2,493: 1987–2020
S	single or two-station location	Unset		not an event type	2,215: 1994–2020
I	induced	"*known fluid injection*" or "*known reservoir loading*"	kk, kw		513: 1988–2020
G	ghost	"*known not existing*"	ku		8: 1627–1964
T	teleseism	"*known earthquake*"	ke		3: 2011–2016
X	controlled explosion	"*known controlled explosion*"	kg		1: 1979

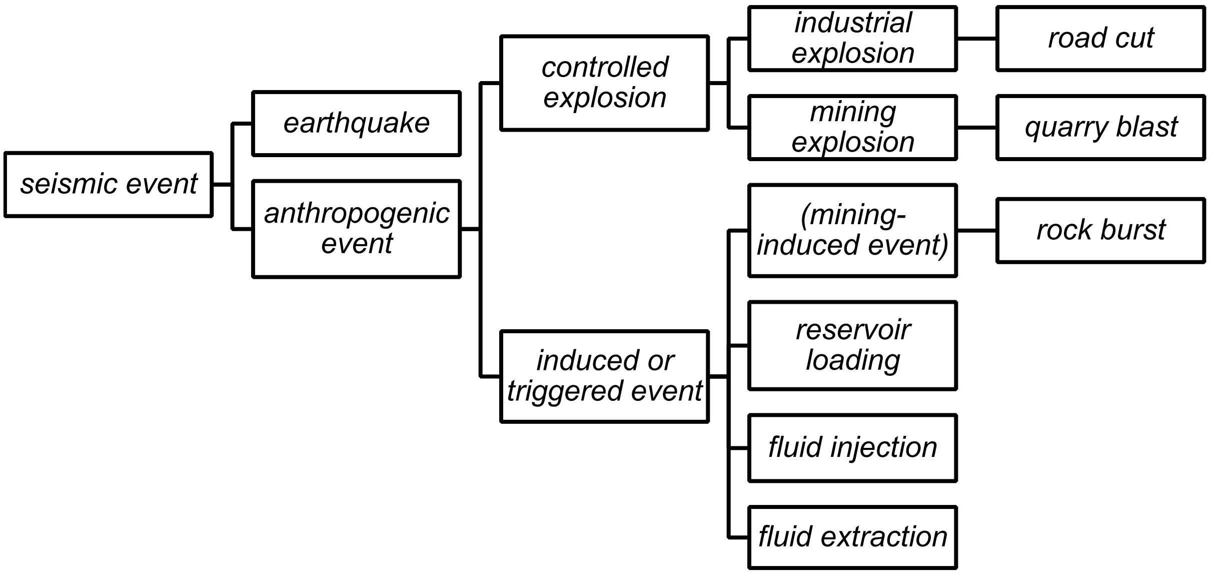

Figure 1: Hierarchy of common event types used in the NEDB. See Figure 3 for the full hierarchy. Parentheses around "mining-induced event" indicate that it is an implied super-type of "rock burst", one which is not supported by QuakeML 1.2. See text for discussion.

QuakeML is the de facto standard for seismic event metadata, and is supported by many important software packages, including ObsPy (Beyreuther, et al., 2010) and SeisComP (Gempa GmbH, 2021). The available QuakeML event types are rigidly enumerated yet relatively comprehensive. Importantly, event types can be qualified with "suspected" or "known", reflecting both the sometimes unavoidable uncertainty, and the provisional nature of some assessments.

The coding and hierarchy of Storchak, et al. (2012) was developed in cooperation with three large seismic datacentres: the U.S. Geological Survey National Earthquake Information Center (NEIC), the International Seismological Centre (ISC) and the European Mediterranean Seismological Centre (EMSC). It is compatible with the IASPEI (International Association of Seismology and Physics of the Earth's Interior) Seismic Format (ISF) used at the ISC. The hierarchy of common event types is shown in Figure 1, while the full hierarchy is given in Appendix A. It should be noted that the hierarchy has been modified somewhat, to improve logical consistency and accommodate current and future needs at CHIS. For example, we consider a "*road cut*" to be a sub-type of an "*industrial explosion*" instead of a sub-type of a "*mining explosion*". Further, we have added an implied "mining-induced event" as a super-type of "*rock burst*". This is necessary because there exist other types of mining induced or triggered events that are not rock bursts, such as cavity collapses, and slip on faults adjacent to the mine. Other differences are discussed in Appendix A.

Table 1 summarizes the recommended mapping between NEDB eqtype and QuakeML event types. Note that for some NEDB eqtype values, there are many QuakeML event types that map to it, most notably "*mining explosion*", "*quarry blast*" and "*road cut*" are all sub-types of "*controlled explosion*". Table 1 also highlights a few problems with the NEDB schema, namely that no eqtype corresponds to a "*suspected fluid injection*" or "*suspected reservoir loading*" event and that eqtype 'S' expresses uncertainty in the location and is not properly-speaking an event type. Furthermore, although the most common event types representable as NEDB eqtype have clear mappings to QuakeML, the NEDB schema cannot capture some types of seismic events, which, while rare, have been recorded in Canada, including landslides, cryoseisms, bolides, hydroacoustic events and plane crashes.

In the main body of this report, the focus is on giving detailed procedure for common event types. Appendix A deals with rare event types, and the focus is on definitions and examples rather than detailed criteria. The QuakeML nomenclature is preferred throughout, and quoted italics, e.g. "*known earthquake*", are used when the emphasis is on the QuakeML type rather than the general concept.

General Procedure

This section gives an overview of the event type discrimination procedure used in routine processing for the common event types in the NEDB.

Conceptually, the discrimination process has two phases. In the first phase, the most probable event type is determined, and if the event does not meet the criteria for a "*suspected anthropogenic*" event of some specific sub-type, then it is categorized as a "*known earthquake*". In the second phase, upon consultation with third parties or review of other types of data, suspected anthropogenic events may be upgraded to "known", or assigned a different type.

Phase 1: Determination of most probable event type

The first phase of event discrimination considers three main questions:

1. Is there evidence that the event was shallow or deep?
2. Do the waveforms have the characteristics of a ripple-fired blast, or an earthquake?
3. Did the event occur near an anthropogenic source, at a time when anthropogenic events can be expected?

For example, if the event was shallow, the waveforms have the characteristics of a blast, and the event occurred near a quarry during daylight hours, then the event is likely a blast. If, on the other hand, the event was deep, has the waveform characteristics of an earthquake, was far from potential anthropogenic sources and occurred in the middle of the night, then the event is likely an earthquake.

A skilled analyst can rapidly classify the majority of events – as earthquakes or blasts – using these criteria; however, the most difficult discrimination tasks are those for which not all of the criteria are satisfied.

For example, if an event occurs near an industrial facility capable of inducing or triggering seismic events, there is evidence that the event is shallow (or the evidence is unclear), and the waveforms do not have the characteristics of a ripple-fired blast, then the event might be an induced or triggered seismic event. Similarly, if an event might be shallow, and has the characteristics of ripple firing, but is not near any known quarry or mine, then the event might be a construction blast.

Figure 2 shows the first phase of event type discrimination for common event types (see Appendix D for an equivalent diagram in French). While this flowchart suggests that the first phase is a sequential process, it is not. For example, the proximity of an event to some facility or its explosive nature may be noted well before its depth is assessed. In fact, analysts frequently treat the available information holistically. Nevertheless, the flowchart does highlight the prime importance of the assessment of depth, evaluation of waveform characteristics, and the proximity of the source in time and space to various kinds of industrial activity.

It is particularly difficult to assess source mechanism and depth for events which are small and/or distant from the densely instrumented parts of the seismograph network; in these cases many branches of the flowchart may be traversed before finding a hypothesis which fits the data. Rare event types are only considered after multiple iterations of this procedure or when external reports of an incident become available. The second phase of the discrimination procedure, confirmation of event type (going from "*suspected*" to "*known*"), has criteria that depend on the event type, for example a mine may confirm a mining-induced event.

Note that this first phase treats events in isolation from each other; statistical analyses of populations of events are not considered for this initial assessment.

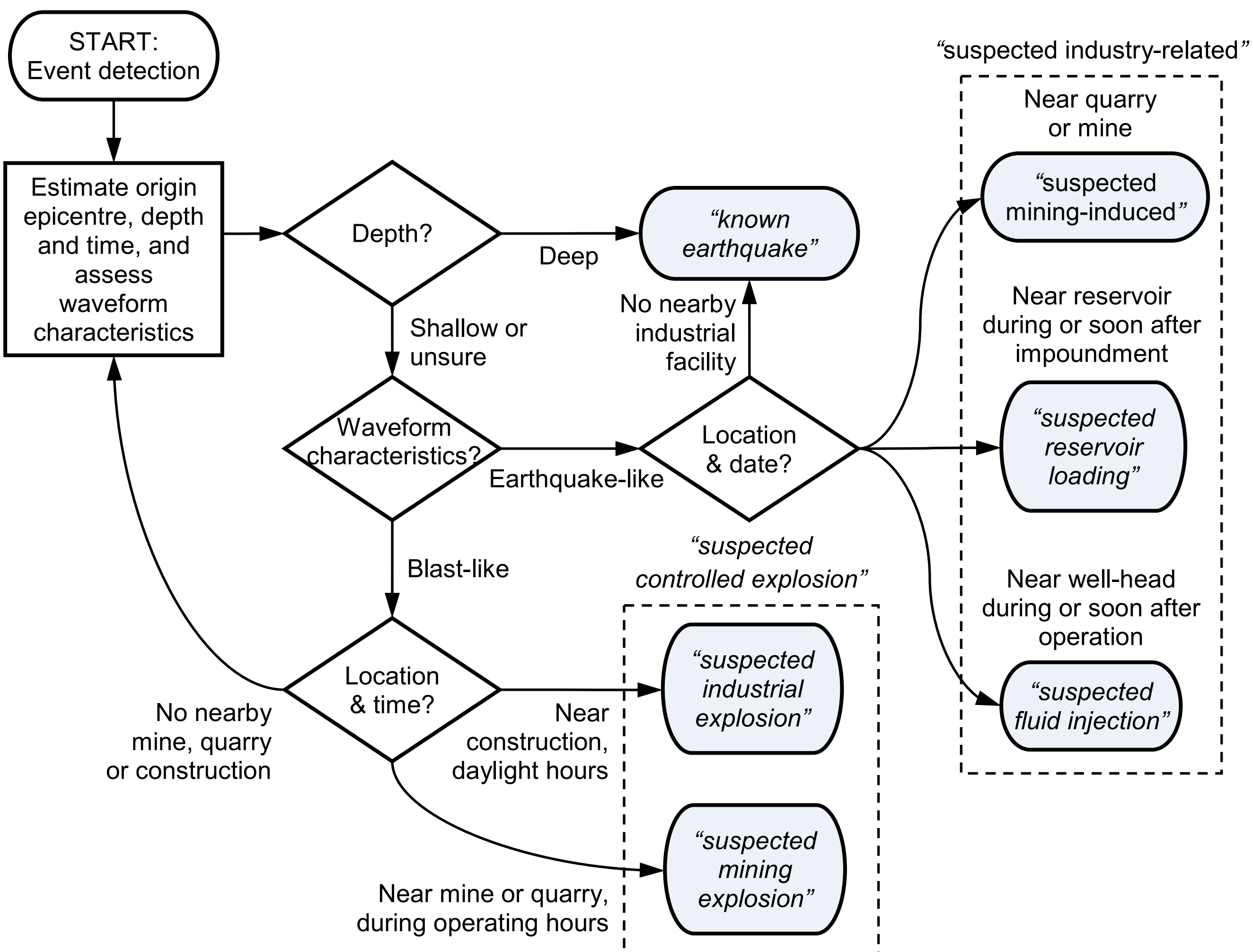

Figure 2: Determination of most probable event type. This flowchart accounts for routine event type discrimination of the vast majority of events in the NEDB. The criteria for assessing depth, waveform characteristics and spatiotemporal proximity are outlined in the text. Note that for events which are shallow or of uncertain depth, blast-like, and not near an industrial facility, there is a loop back which indicates that origin and waveform characteristics are to be reassessed.

Depth

In the context of using depth as a discriminant, the key question is whether or not the event may be anthropogenic in origin, and therefore whether or not the event is shallower than about 5 km. The depth of a seismic event can be estimated by a variety of methods, but regional monitoring networks impose significant constraints on what is possible.

Conservative practice for depth estimation using direct phase arrivals is that such estimates are only considered accurate when the distance to the nearest seismograph stations is less than twice the depth (Havskov, Bormann, & Schweitzer, 2009), e.g. within 36 km for an event at 18 km depth. At CHIS, the current practice is not so strict. For example, in eastern Canada it is typically only required that the nearest three stations be within 100 km. Even so, there are few regions in Canada where station density is sufficient for depth estimation using direct phase arrivals.

Failing this, depth can sometimes be estimated at a single station from observations of the difference in arrival times between specific pairs of direct and indirect phases (the latter called depth phases). The utility of depth phase methods is, however, limited to larger magnitudes and relatively narrow ranges of epicentral distances. For example, the regional depth phase sPmP is well developed between 200 and 300 km for an event at 12 km depth (Ma, 2010) and magnitudes greater than 2 (Veronika Peci, personal communication).

Moment tensor inversion can constrain depth but without detailed local velocity models it is only reliable above magnitude 4, and therefore not useful for routine discrimination of earthquakes from blasts.

For the majority of events, being small, the only available indicator of depth during routine processing is crustal Rayleigh (Rg) waves. The observation of Rayleigh waves in the band 1-5 Hz is a good indicator, for both explosions and natural earthquakes, that the depth is less than 3 km (Bowers & Selby, 2009). When crustal Rayleigh waves are observed, and no better estimate of depth is available, seismic analysts may fix the depth of the hypocentre at 2 km.

Waveform characteristics

An experienced analyst can usually distinguish ripple-fired blasts from natural or induced earthquakes based on a qualitative assessment of waveform characteristics in the time domain.

Most controlled explosions employ ripple firing to enhance fracturing of the rock and to reduce ground motions close to the blast (Carr & Garbin, 1998). Ripple firing consists of loading explosives into holes drilled in a precise pattern, and detonating them sequentially with delays typically between 10 ms and 0.5 s, and typically lasting 0.5–5 s. Idealized explosive sources embedded in isotropic homogeneous media produce only compressive waves, but in practice shear waves are also produced (Bowers & Selby, 2009).

In contrast, earthquakes in the same range of magnitudes as controlled blasts (magnitude < 4) have source times shorter than 0.1 s. Earthquake sources are typically well modeled as double-couples, radiating significantly more energy as shear waves than as compression waves.

These characteristics of controlled explosions and earthquakes give rise to two key characteristics that are routinely assessed in seismograms:

1. First arrivals from a ripple-fired blast will tend to appear emergent, with the amplitude ramping up over the course of several seconds, and complex, with little or no decay in the P-wave coda. An exception is that at stations very close to the quarry, first arrivals can appear impulsive. In contrast, first arrivals from an earthquake tend to be impulsive and simple, with a clear P-wave coda decay. Exceptions include stations at azimuths near minima in the radiation pattern, and at great distances where scattering and multi-pathing take over, resulting in emergent arrivals.

2. The ratio of S to P wave amplitudes will tend to be much larger for earthquakes than for blasts, and S-waves may be barely visible above the P-wave coda for blasts. A high pass filter is typically the most diagnostic, but analysts must remain alert to the fact that the optimal time windows, filter bands and thresholds for spectral ratio discriminants can vary greatly from one region to the next. Regional variability of spectral ratio discriminants may be attributed to source rock characteristics (Walter, Mayeda, & Patton, 1995), variability in ripple-firing setup (Kim, Aharonian, Lerner-Lam, & Richards, 1997), source depth (Myers, Walter, Mayeda, & Glenn, 1999), near-source scatterers (Gupta & Patton, 2008) and path effects (Bowers & Selby, 2009).

The analyst should avoid focusing on a single station, and should instead look for patterns in these characteristics among all of the available data.

In spite of the caveats noted, an experienced analyst can generally distinguish small earthquakes from ripple-fired blasts quickly, by looking for the above waveform characteristics.

When firing delays are constant, ripple-fired blast spectra can exhibit scalloping (Hedlin, Minster, & Orcutt, 1989) or other features (Ursino, Langer, Scarfi, Grazia, & Gresta, 2001), but the examination of spectra is not generally part of routine processing at CHIS. Explosions have predominantly compressive (upward) P-wave arrivals, but ripple firing and a relatively sparse regional network make it difficult or impossible to obtain enough clear first motion polarities for an identification.

If the focal mechanism can be estimated, then this can be an important discriminant. Unfortunately, moment tensor inversion using regional seismograph networks is only viable for events larger than approximately magnitude 4, and so not useful for routine discrimination of earthquakes from blasts.

Spatiotemporal proximity

In the detailed criteria for common event types below, precision is given to notions of proximity in space and time for anthropogenic events.

A database of industrial facilities with production in the previous year, including coordinates, is produced and published annually by NRCan (LMS; CER, 2021), and incorporated into the Atlas of Canada (see Internet Sources). This is an excellent source for up-to-date information about mines, and oil and gas fields. For quarries, because they are regulated provincially, there is no single authoritative source of information (see Internet Sources).

There are four main sources of uncertainty that must be considered when assessing the spatial proximity of an event to an industrial facility:

1. Epicentral uncertainty due to uncertainty in arrival time picking. Most modern location algorithms produce an epicentral uncertainty ellipse derived from the pick time uncertainties.
2. Epicentral uncertainty due to uncertainty in the velocity model. For routine processing, simple 1D models are typically used; errors in these models can produce significant epicentral errors. These errors are to first order proportional to the distance to the nearest stations, and can vary from less than a kilometer in densely instrumented regions to tens of kilometers in sparsely instrumented regions. Velocity model errors are exacerbated by poor azimuthal coverage.
3. Uncertainty in the extent of the industrial facility. Underground mines can extend up to a few km from the mainshaft. Directional drilling associated with fluid injection can extend even further. Satellite imagery may not even be up-to-date enough to reflect the current extent of surface mines and quarries, nor indicate the status of operations (i.e. active, or inactive).

4. Uncertainty in the maximum distance at which events can be induced outside underground facilities. The maximum distance varies with the type of industrial activity and the geology.

The overall uncertainty in spatial proximity is a combination of all of the above, varying greatly from one event type to another and from one region to another.

Temporal proximity at its most basic means that in order for an event to be caused by an anthropogenic source, it must occur *after* the associated industrial activity. In addition, the maximum delay after which an event can be caused after the cessation of industrial activity depends on the event type.

Phase 2: Confirmation of event type

An event type is "*suspected*" if the particular event type has not yet been confirmed or is otherwise uncertain. This is mainly used for events related to industrial activity that have not been confirmed by a third party, or for which the assessment criteria are not completely clear.

An event type is "*known*" when there is a high degree of confidence as to the nature of the source of the event. The criteria for progression from "*suspected*" to "*known*" differ for different event types. For mining explosions and quarry blasts, it is enough that the event meets the criteria for these event types particularly well. For anthropogenic events which are not controlled explosions, such as fluid injection or mining induced or triggered events, the standard for progressing from "*suspected*" to "*known*" is stricter, requiring consultation with a third party.

It is critical that the criteria for assigning a blast as "known" not be onerous, because these types of event outnumber most other types, and are of the least seismological interest.

Specific criteria for confirming each event type are given in the next section.

Detailed Criteria for Common Event Types

Earthquake

A seismic event is categorized as a "*known earthquake*" if it has the waveform characteristics of an earthquake and is not suspected to be an induced or triggered seismic event.

When there is significant epicentral uncertainty, (e.g. when arrivals can only be picked at one or two stations and there is no waveform similarity to other, better-recorded events) an event may be classified as a "*suspected earthquake*". This should only happen when no other event type is more plausible (e.g. if the waveform characteristics have any resemblance to a ripple-fired blast, then "*suspected controlled explosion*" could be more appropriate).

Controlled explosion

Controlled explosions are intentional chemical explosions, designed to minimize ground motion and danger to bystanders while serving goals such as excavation, fracturing and demolition, or as part of an experiment. Conceived as such, in the hierarchy of Figure 1 (and Appendix A), with the exception of experimental explosions, controlled explosions generally employ ripple firing. The super-type "*controlled explosion*" should not be assigned to an event – one of the sub-types should be selected instead – but it may be useful for database queries.

The most common type of controlled explosion detected on seismograph networks are mining explosions and quarry blasts, but construction blasts including road cuts are also common.

Mining explosion, quarry blast

An event is initially classified as a "*suspected mining explosion*" or a "*suspected quarry blast*" when it has the characteristics consistent with a shallow ripple-fired blast, as described in the "Depth " and "Waveform characteristics" sections above, and:

a) Epicentre located near a known facility. Typically this means within 5-10 km, less if several stations are located near the source, more if nearest station is quite distant or the azimuthal coverage, and hence, hypocentral accuracy is poor. Two types of sources are frequently used to identify facilities:
   - satellite imagery for quarries & mines with surface expression (e.g. Google Maps)
   - governmental databases of mines (LMS; CER, 2021) and quarries (see Internet Sources)

b) Origin time during daylight hours (quarry) or at a shift change (mine). Signature times vary greatly between facilities and seasons. In general, it is not permitted to detonate surface explosions outside of daylight hours, while mines blast at shift changes for safety reasons. Origin time can be a strong discriminator when the facility keeps to a strict and well-known schedule. Conversely, origin time can be a very weak discriminator when the schedule is not known, particularly for events near the end of the working day. Finally, although an origin time during daylight hours or at a shift change is not sufficient to prove that an event is a blast, an event which occurs in the middle of the night (near a quarry) or away from shift changes (near an underground mine) is very likely not a blast.

For quarries, or mines with no underground component, "*quarry blast*" is preferred to "*mining explosion*", although the latter is also correct.

The certainty associated with a mining explosion depends on the degree to which the typical characteristics are evident and the depth of the associated source. There are three common cases:

1. For explosions not near an identified facility, the type will likely remain a "*suspected mining explosion*".
2. For events with all or nearly all of the characteristics of a mining explosion, and for which the identified facility is a quarry or an open pit mine, the event shall be identified as "*known mining explosion*". In general, these events are not pursued further with the facility operator.
3. For events with most or all of the characteristics of a mining explosion AND for which the identified facility is an underground mine, in the absence of additional information the event will be identified as a "*suspected mining explosion*". Several further sub-cases exist, however:
   a. If a blasting notification was received from a mine or quarry operator, an event can be labeled as a "*known mining explosion*". In this case, a comment attached to the event should explain that a blast notification was received.
   b. If open lines of communication exist with the mine operator, and time permitting, confirmation of the type of mining event will be sought. The event may then be marked as "*known mining explosion*" or a "*known rock burst*". In this case a comment attached to the event should explain what was confirmed and by whom.
   c. An event may be labelled as a "*known mining explosion*" if it matches the characteristics of a previous, confirmed explosive event at the same facility.

For an experienced analyst, further characteristics of mining explosions can be diagnostic of events originating at a particular mine or quarry near a particular set of seismographs. These characteristics, however, do not generalize well, and for that reason are not considered part of the main discrimination procedure. Such characteristics are listed below for completeness.

e) There are no blasts of magnitude 4 or greater in the NEDB. Surface blasts in the large iron ore mines near Labrador City can reach magnitude 3.5. Few, if any, mines outside southeastern British Columbia, southwestern Alberta, northern Minnesota and the Labrador City area have produced blasts above magnitude 3. Blasts in underground mines rarely exceed magnitude 3. Nonetheless, it would be irresponsible to categorise an event as an explosion based on the magnitude being below a magnitude threshold.
f) Mining explosions at a number of sites in Canada occur in multiples. When the delay between a detonator and the main charge (typically only observable at the nearest station) is on the order of a second, this can be observed as multiple arrivals at a nearby station. Some mines use multiple main charges with separation in time on the order of tens of seconds. Finally, an explosion can produce a rockfall or rock burst after a short delay. Although these characteristics are sometimes observed, on their own they are not useful as discriminators because the techniques used vary from one facility to the next and because natural seismicity can have complex source waveforms and/or produce emergent arrivals. Furthermore, aftershocks can happen immediately after main shocks.
g) Visual or aural confirmation of activity in the field is sometimes available.

Industrial explosion (construction blast), road cut, blasting levee

The intent of this category is to separate construction blasts – particularly those excavating road cuts - from mining and quarry blasts in the catalogue, in order to facilitate subsequent research.

Because road cuts and construction blasts are generally ripple-fired, their waveform characteristics are similar to those of an open-pit mining explosion or quarry blast. The difference is that that the epicentre may not be near a mine or quarry. In the case of a road cut, the first indicator is generally that the epicentre of a surface explosion is near an existing highway.

It is typical for epicentres of "*road cut*" explosions to move progressively along the road as construction proceeds.

Confirmation that explosives are being used in the area can come from information posted by ministries of transportation on public web sites (e.g. Internet Sources listed below). Individual events typically would not be confirmed, so the initial coding of "suspected industrial explosion" may frequently persist.

Induced or triggered event (industry-related)

Although this super-type is not normally assigned to an event in the NEDB during routine analysis, the SOC will use the term "suspected industry-related" if there is uncertainty as to the event type when communicating with government operations, media or the public.

For the most part, the seismograms of these events look like those for shallow, natural tectonic earthquakes. The three types of induced or triggered event that are commonly assigned in the NEDB are detailed below.

In cases where the event is suspected to be induced or triggered, but the depth cannot be estimated from seismograms, seismic analysts may fix depth of the hypocentre at a suitable pre-determined depth, typically 1 km.

Rock burst (mining-induced event)

The category of "*rock burst*" is an umbrella for a number of different types of occurrence that would best be described as mining-related or "mining-induced" events. The source mechanism can be double-couple, explosive or implosive. The source location can be at some distance from the excavated volume of the mine, at the rock face or in a support structure of the mine (Hasegawa, Wetmiller, & Gendzwill, 1989). The origin time can be during operation or after the mine has ceased operation; in particular mines that have recently been allowed to flood are expected to produce induced events. Unfortunately, “mining-induced” is not among the types enumerated by QuakeML as of version 1.2, so the term “*rock burst*” is used instead.[2]

When a SOC conveys an assessment to government operations, media or the public the term “mining-induced” event is strongly preferred because of potential legal implications of the term “rock burst”. The designation of an event as a “rock burst” within the NEDB is intended to facilitate exchange of seismological data for research purposes; it shall not prejudice any legal question as to the nature of the event.

Because of the variability in source mechanism, and because rock bursts can happen virtually simultaneously with mining explosions, it can be difficult to characterize the seismograms produced. Note as well the caveats relating to transportability of discriminants in the “Waveform characteristics” section above.

An event is initially classified as a “*suspected rock burst*” when it has characteristics consistent with a shallow earthquake, as described in the “Depth ” and “Waveform characteristics” sections above, and:

a) Epicentral uncertainty ellipse (90% confidence) within 10 km or an epicentre (uncertainty unknown) within 20 km of a mine that is currently producing or recently decommissioned.

The NRCan map of producing mines (LMS; CER, 2021) for a given year, is a comprehensive list of mines which produced in that year.

If open lines of communication exist with the mine operator, and time permits, confirmation of a “*suspected rock burst*” event will be sought.

An event originally labelled as a “*suspected mining explosion*” may be re-classified as a “*known rock burst*” upon consultation with a mine operator. Details regarding the confirmation of event type should be documented in the internal comments.

Fluid injection

Seismicity triggered by fluid injection is most often related to operations associated with enhanced recovery and production of oil (Horner, Barclay, & MacRae, 1994) and the development of unconventional oil and gas, including hydraulic fracturing (a.k.a. “fracking”) (Farahbod, Kao, Walker, & Cassidy, 2015; Schultz, et al., 2020) and wastewater disposal (Ellsworth, 2013). Outside Canada, it has also been associated with CO_2 sequestration and geothermal power generation.

An event is initially classified by CHIS as a “*suspected fluid injection*” when it has characteristics of an earthquake, as described in the “Waveform characteristics” section above, and:

a) Epicentre in a region with historically low levels of seismic activity,
b) Epicentral uncertainty ellipse (90% confidence) within 10 km or an epicentre (uncertainty unknown) within 20 km of an installation (e.g. a well head) that has been known to be

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[2] Some mining-induced events would be more precisely characterised as a “*mine collapse*”. However, there is rarely sufficient information available to distinguish a rock burst from a mine collapse in routine processing, so the use of “*rock burst*” is encouraged instead. It should be noted that “*mine collapse*” is considered a sub-type of “*collapse*” by Storchak (2012), along with “*building collapse*”, but at CHIS it is treated it as a sub-type of “mining-induced” event (see Appendix A).

active within the last 5 years or of previous "*known fluid injection*" induced events within the same period of time, and

c) Not demonstrably deeper than 10 km.

The NRCan map of oil and gas fields (LMS; CER, 2021) for a given year is a comprehensive list of wells that produced in the previous year. Updated information should regularly be sought from provincial regulators, e.g. active disposal wells (BCOGC, 2019).

The identification of events as "*known fluid injection*" induced only occurs with confirmation by the provincial or territorial energy regulators (e.g. British Columbia Oil and Gas Commission, Alberta Energy Regulator, Northwest Territories Department of Environment and Natural Resources). Any event that is at least magnitude 4 or reported as felt is immediately investigated by regulators.

The SOC is required to contact the regulator whenever a significant event is "*suspected fluid injection*" induced. Prior to confirmation by a regulator that an event is "*known fluid injection*" induced, the SOC will use the term "suspected industry-related" when communicating with government operations, media or the public.

Currently, regions with historically low seismicity and large-scale fluid injection activities include the Horn River Basin, Liard Basin, and the Montney Play in British Columbia, the Duvernay Play and Basal Banff/Exshaw Formation in Alberta, and Norman Wells in Northwest Territories. See Appendix B: Current areas of interest for fluid injection induced events for more information.

Reservoir loading

Events due to reservoir (water) loading are also known as "reservoir-triggered", "reservoir-induced" or "impoundment-induced" seismicity. Historically, in Canada, the largest "*reservoir loading*" induced earthquake was a magnitude 4.1 (MN) event in 1975 near the dam which impounds the Manic-3 reservoir in Quebec.

Typically, induced seismicity will occur when the water level changes by 50 m or more and the activity may last for many months or years. Eventually, the activity decreases as time passes, and events rarely occur years after the impoundment.

Distinguishing these events from blasts and tectonic earthquakes is challenging. The job is made easier when seismographs are located near the reservoir or when times and locations of blasting can be confirmed.

An event will be categorized upon initial analysis as "*suspected reservoir loading*" when it has characteristics consistent with a shallow earthquake, as described in the "Depth " and "Waveform characteristics" sections above, and:

a) Epicentre in a region with historically low levels of seismic activity,

b) An epicentral uncertainty ellipse (90% confidence) within 10 km or an epicentre (uncertainty unknown) within 20 km of the outline of impounded water or penstock tunnel, and

c) Occurs within 10 years of the depth of the impounded water reaching 30 m.

A dedicated study is generally required to confirm that an earthquake is due to reservoir loading, and to classify the event as "*known reservoir loading*".

Currently, in Canada, the only areas with potential for seismicity due to reservoir loading are the Eastmain and La Romaine reservoirs in Quebec and Muskrat Falls in Newfoundland and Labrador. See Appendix C: Current areas of interest for reservoir loading induced events.

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Séismes Canada (last accessed 2021-08-31): https://seismescanada.rncan.gc.ca/
CNSN Station Book (last accessed 2021-08-31):
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http://atlas.gc.ca/mins/

Provincial/Territorial

Alberta – Petroleum, natural gas and oil sands map (last accessed 2021-08-31):
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https://www.quebec511.info/fr/diffusion/etatreseau/default.aspx
Hydro-Québec – Centrales hydroélectriques (last accessed 2021-08-31):
https://www.hydroquebec.com/production/centrales.html

Other

United States –Tsunami Warning Centres (last accessed 2021-09-23):
https://tsunami.gov/

Appendix A: Hierarchy of Event Types

The main purpose of assigning an event type is to distinguish “natural seismicity” (i.e. tectonic earthquakes) from other anthropogenic and non-tectonic sources (Fujita & Sleep, 1991). This distinction is crucial to the proper assessment of seismic hazard. Cataloguing of non-earthquake seismic events furthermore aids subsequent event type discrimination efforts. The proliferation of non-earthquake event types is in part an attempt to answer, more accurately, the question: If it wasn’t a natural tectonic earthquake, what was it?

This appendix sets out a hierarchy of event types, and a set of single-letter codes that covers most of these types. There follow basic definitions, and where possible examples, of the rarer event types so that they may be used in the NEDB.

Full Hierarchy

Figure 3 shows the full set of QuakeML event types available to an analyst, grouped in a logical hierarchy of super-types and sub-types similar to Storchak, et al. (2012). There are four main differences between this hierarchy and Storchak, et al. (2012):

- The “*rock burst*” and “*mine collapse*” types are considered to be sub-types of an implied “*mining-induced event*” type. Until a “*mining-induced event*” is added to the QuakeML types, “*rock burst*” must be treated as if it were this super-type.
- The hierarchy of explosions has five layers instead of three. For example, “*controlled explosion*” is considered a super-type of industrial, experimental and mining explosion, which are all typically ripple-fired explosions. Also of note is that “*blasting levee*” is considered here to be an “*industrial explosion*” instead of a “*mining explosion*”.
- The “*ice quake*” type is considered to be a subset of an implied “*cryoseism*” super-type, along with a proposed new “*frost quake*” type. Until a “*cryoseism*” is added to the QuakeML types, “*ice quake*” must be treated as if it were this super-type, so that it includes “*frost quake”*.
- It can be misleading to classify “*sonic boom*” as a non-anthropogenic event.

The hierarchy of event types is currently not built into FDSN web services for requesting event metadata, therefore if a person wants to request all events of a given super-type (e.g. “*controlled explosion*”), they must consult Figure 3 and explicitly enumerate all of the sub-types (e.g. “*industrial explosion*”, “*road cut*”, “*blasting levee*”, “*experimental explosion*”, “*mining explosion*”, “*quarry blast*”).

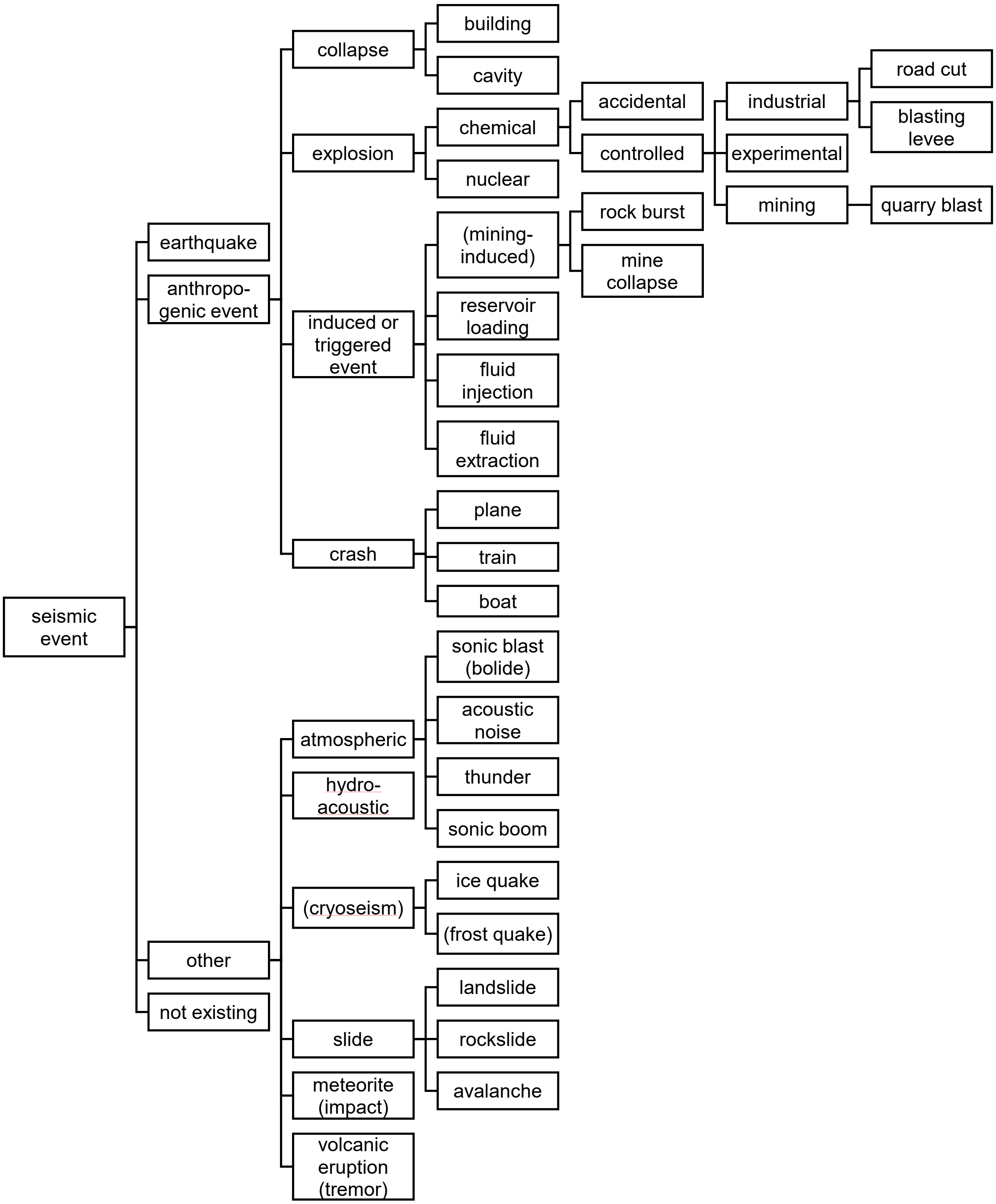

Figure 3: Hierarchy of available event types used in the NEDB. See Figure 1 for a simplified hierarchy covering the most common types. Parentheses words or types which should be considered “implied” though not actually supported by QuakeML 1.2 (see text for discussion). Single-letter codes are as per Storchak et al. (Storchak, et al., 2012).

Two-Letter Codes

The two-letter codes first proposed by Storchak, et al. (2012) for QuakeML eventType (first letter) and eventTypeCertainty (second letter) are to be used. Table 2 summarizes the event type codes,

Table 2: Event type codes and QuakeML equivalents. Not all of the codes defined by Storchak, et al. (2012) are used in the NEDB, but they are nonetheless listed here to indicate that they may be used in other earthquake catalogues and are thus reserved. Some of the single-letter codes encompass multiple QuakeML types; in each case the preferred equivalent is indicated. Note that <space> denotes the space character, ASCII 32. The “preferred” event type listed is to be used when converting from letter codes to QuakeML event type.

Code	Not used (reserved)	QuakeML eventType		Non-QuakeML synonyms
		Preferred	Equivalents or sub-types	
e		earthquake		
a	χ	anthropogenic event		
x		explosion		
m		mining explosion	quarry blast	
d		industrial explosion	road cut blasting levee	construction blast
f	χ	accidental explosion		
g	χ	controlled explosion		
h	χ	chemical explosion		
j		experimental explosion		
n		nuclear explosion		
i		induced or triggered event		industry-related
r		rock burst	mine collapse	mining-related mining-induced
w		reservoir loading		
k		fluid injection		
q		fluid extraction		
p		crash	plane crash train crash boat crash	
o	χ	other event		
l		landslide	rockslide slide debris avalanche	
b		avalanche	snow avalanche	
s		atmospheric event	sonic boom sonic blast acoustic noise thunder	bolide
z		ice quake		frost quake cryoseism
t		meteorite		meteorite impact
v		volcanic eruption		volcanic tremor
c		collapse	cavity collapse building collapse	
y		hydroacoustic event		underwater event
u		not existing		
<space>		not reported	unset	

and indicates that for some super-types, although there is a single-letter code reserved, one of the sub-types should be assigned, when appropriate, instead.

Table 3 summarizes the event type certainty codes. Although Storchak, et al. (2012) propose "u" for "*unknown*" and "n" for "*not reported*" as event type certainty, these are not valid event type certainty values in QuakeML 1.2. For clarity, it is therefore recommended that "u" and "n" not be used in the NEDB.

Rare Seismic Event Types

In this section, rare event types are described, that is, those not covered in the main body of this report, under "Detailed Criteria for Common Event Types".

Anthropogenic event

The categories of events related to human activity (i.e. anthropogenic events) used in the NEDB are clearly separated from other types in Figure 3. Thorough investigation of events of some of these types can yield important forensic information.

The super-type "*anthropogenic event*" should never be assigned, itself; instead, one of the sub-types should be used. However, it could be a useful category for database queries.

Explosion

While the super-category of "*explosion*" itself is not normally assigned in the NEDB during routine processing, it may be useful for a seismologist on call, when conveying the nature of the event to government operations, media or the public, when the type of explosion is not known.

For the purpose of this classification scheme, explosions are anthropogenic. While volcanic eruptions can include explosive events, such an event would be classified as a "*volcanic eruption*" rather than an "*explosion*".

Experimental explosion

One important kind of experimental explosion is a controlled explosion that is part of a seismic experiment. They can be extremely useful for investigating seismic propagation within the earth, because the hypocentre and yield can be very accurately estimated. An example in the NEDB are shots related to the Lithoprobe experiment: these events were classified as "B - blast" prior to the adoption of the QuakeML event types.

Confirmation of this event type would normally come from the primary investigator or publications.

Nuclear explosion

Nuclear explosions have the characteristics of an explosion, but are typically larger than chemical explosions, and will not have the emergent onset and waveform complexity characteristic of ripple-fired explosions. Key discriminants include a shallow hypocentral depth, ratio of body- to

Table 3: Event type certainty codes and QuakeML equivalents. Not all of the codes defined by Storchak, et al. (2012) are used in the NEDB, but they are nonetheless listed here to indicate that they may be used in other earthquake catalogues and are thus reserved.

Code	Not used (reserved)	QuakeML eventTypeCertainty
k		known
s		suspected
u	✗	
n	✗	

surface-wave magnitudes and ratio of high-frequency P to S energy, but no single method consistently works for all regions. Confirmation of this event type typically comes after analysis of data from additional sources, especially the detection of radioactive by-products (Bowers & Selby, 2009).

Verification of nuclear explosions is the responsibility of the Comprehensive Test Ban Treaty Organization.

Accidental explosion, controlled explosion, chemical explosion

While these types of explosions may be useful for grouping events with similar characteristics, and they may be seen in databases from other agencies, they should not generally be assigned to specific events in the NEDB. Instead, preference should be given to specific explosion sub-types.

Induced or triggered event (industry-related)

Fluid extraction

The extraction of both hydrocarbons (Segall, Grasso, & Mossop, 1994) and water (González, Tiampo, Palano, Cannavó, & Fernández, 2012) from underground has been shown to cause subsidence and to contribute to the triggering of earthquakes. Note that although hydraulic fracturing inevitably involves extraction as well as injection, these events would typically be classified as related to fluid injection.

Aside from identification of shallow hypocenters, there is little to distinguish a fluid extraction induced earthquake from a “natural” tectonic earthquake. Thus, the demonstration that an earthquake has been induced by fluid extraction is likely to involve a detailed study of prior seismicity and modeling of induced stresses. Such events furthermore have not yet been observed in Canada. For these reasons, this event type is unlikely to be assigned, even as “*suspected*”, on preliminary analysis.

Crash, plane crash, train crash, boat crash

Prior to the adoption of the procedures documented here, for lack of a suitable event type code, no events were identified as plane, train or boat crashes in the NEDB. Such events are rather impulsive, and generally recorded too poorly to be located with any accuracy. Their inclusion in the NEDB would rely on secondary proof of occurrence, such as eyewitness reports coinciding with time and approximate location of seismic records.

A notable example is the Swissair crash (44.409°N, -63.974°W, 1998-09-03 01:31:21 UTC). Seismic recordings at CNSN stations HAL and LMN permitted estimation of impact time and velocity (McCormack, 2003). This event was misleadingly classified as a “B - blast” in the NEDB, prior to the adoption of the QuakeML nomenclature.

Collapse, cavity collapse, building collapse, mine collapse

When a large structure collapses, seismic waves are generated. The collapse of the World Trade Center towers on September 11, 2001 was detectible on seismographs up to 500 km away (Rollings, 2015).

Cavity collapses and mine collapses are underground events. An example of a non mining-related cavity collapse event is the collapse of the cavity produced by an underground nuclear test (Chiang, et al., 2018). Such events are effectively “aftershocks” of underground nuclear explosions.

Although mine collapses are relatively common, it is rare that they can be distinguished from other types of mining events such as rockbursts (inside the mine) and induced earthquakes (near but outside the mine). For lack of a clear super-category in the QuakeML schema (i.e. a "mining-induced" event) it is recommended that a "mine collapse" be coded as a "*rock burst*", because they can be difficult to distinguish seismologically and because it is rare that an operator will confirm the distinction.

Other event

According to the hierarchy of Storchak (2012) the "*other*" category comprises all seismic events that are neither natural earthquakes nor anthropogenic events.

Most of the event types in this sub-classification are unlikely to be assigned during initial analysis, based on waveforms and mapping data alone. More often, they will be re-categorised after further assessment, information published in the news media and journals, or via private communications with other agencies.

Slide, landslide, rockslide

Landslide events include rockfalls, debris flows, and lahars. This event type is not meant to encompass landslides caused by other types of events, since such events would likely be buried within the coda of another event with a different event type (Storchak, et al., 2012).

Large landslides are characterised by a predominance of long-period waves. In contrast to earthquake source mechanisms, which are well modelled by a double-couple of forces, long-period landslide arrivals are well modelled by a single force (Ekström & Stark, 2013). Very large landslides are detectible on regional (Kao, et al., 2012) and global seismograph networks (Ekström & Stark, 2013). Landslides have proven challenging to locate accurately due to the extremely emergent, long-duration nature of the events (Dammeier, Guilhem, Moore, Haslinger, & Loew, 2015). As a result, only large landslides have been located using seismological data.

Landslides are typically confirmed via news media reports or by local or regional emergency management organizations. In remote regions, confirmation can be made with helicopter flyovers or satellite imagery.

The Hope Slide of 1965 is an important case study for event type discrimination. As initially entered in the catalogue, the two events recorded on seismographs in the region were classified as earthquakes, assumed to have triggered the observed landslides and in fact assigned the same location. Subsequently these earthquakes were deemed unlikely to have been capable of triggering the landslides (Wetmiller & Evans, 1989). Finally, it was determined that the observed seismic waves were in fact the signature of the landslide itself (Weichert, Horner, & Evans, 1994). Prior to the adoption of the QuakeML nomenclature, for lack of an appropriate event type, these events were classified as "L - local earthquake" in the NEDB.

Near Canada, landslide-type events are most common in the Yakutat region of southeast Alaska. Prior to the adoption of QuakeML event types, such events were not entered into the NEDB, except occasionally as misidentified earthquakes.

Avalanche, snow avalanche, debris avalanche

Snow avalanches share many characteristics with landslides but are more difficult to detect due to the smaller masses involved and the relatively soft nature of the impacting material. As with landslides, they can occasionally be detected with seismographs, but tend to require a targeted deployment of sensors (Lacroix, et al., 2012). An infrasound signature may be more diagnostic. No avalanches have yet been identified within the NEDB.

Atmospheric event, sonic boom, sonic blast (bolide), acoustic noise, thunder

Atmospheric events are generally only weakly recorded on seismograph networks but they enter into seismic records in part because they are widely heard and reported. The "atmospheric event" type should not normally be assigned to an event; it is preferable to assign one of the sub-types.

A sonic blast, such as one generated by an atmospheric explosion or a bolide, or one generated by an aircraft momentarily exceeding the speed of sound, can be approximated as a point source. They are locatable using standard event location algorithms provided an appropriate velocity model is used (Johnston, 1987). A successful location using the speed of sound at low altitudes combined with reports from eyewitnesses or security cameras would be enough to confirm this event type.

Sonic booms resulting from an aircraft in sustained transonic or supersonic flight produce a "carpet" of direct acoustic arrivals with a distinctive "W" shaped arrival (Cates & Sturtevant, 2002). A secondary effect is coupling via Rayleigh waves, although these can be observed as precursors, because seismic velocities are generally higher than the speed of sound.

Sonic booms resulting from a meteoroid in flight can be well approximated by a line source. Air-to-ground coupling is predominantly direct rather than via Rayleigh waves. (Edwards, Eaton, & Brown, 2008).

Confirmation of sonic booms caused by aircrafts as "*known*" would generally require corroboration by flight authorities.

It should be noted that since both sonic blasts and sonic booms can be non-anthropogenic, it is misleading that the hierarchy of Figure 3 groups the "sonic boom" with other "atmospheric event" types as an "anthropogenic event".

The seismic waves produced by the coupling of thunder into the ground has been recorded on seismographs (Kappus & Vernon, 1991).

It is not clear what is intended by the QuakeML "*acoustic noise event*", so the event type should be avoided.

Ice quake (frost quake, cryoseisms)

Ice quakes occur when a mass of ice is subjected to a rapid change in temperature (Lacroix A. V., 1980), causing stresses that are released when the ice fractures. Two subclasses of cryoseism are sometimes identified: frost-quakes, which occur in frozen groundwater-saturated soil or rock and ice-quakes, which occur in frozen bodies of water. The QuakeML schema would be clearer if it defined a super-type "*cryoseism*" with "*ice quake*" and "*frost quake*" as sub-categories; failing this, the QuakeML event type "*ice quake*" is to be used for all types of cryoseism in the NEDB.

Although shear waves are generated and can be detected in the body of ice itself (e.g. on a glacier), these shear waves do not couple well into competent rock so only P-wave and surface-wave arrivals are expected at distance (Eaton, 2014). Cryoseisms tend to have a smaller felt area than earthquakes of the same magnitude and are more often reported due to their auditory quality than ground motion.

CHIS is frequently asked to comment on such phenomena, even when nothing is detected on the national seismograph network. In this case, the most accurate response is generally to assert that if the event was an earthquake then its magnitude was below the network detection threshold for the region, typically between magnitude 2 and 3.

A historical (but not instrumentally recorded) example in the NEDB is the frost-quake of 1884-01-26 near St. John, New Brunswick (Burke, 2004). Prior to the adoption of the QuakeML event types, this event was classified as eqtype "L", an earthquake in the NEDB; it is more properly a "*suspected ice quake*".

Confirmation of ice quakes and frost quakes can come from physical inspection of the epicentral region.

Meteorite (impact)

Seismic recordings of meteorite impacts are very rare, because the object must either be very large or the impact must be very close to a seismograph station (Edwards, Eaton, & Brown, 2008). Seismograms are usually complemented with non-seismic data: images of the meteor in flight (with appropriate timing and location) are enough to classify the event as “known”, while the physical discovery of the meteorite would confirm the location but not the time of impact.

Note that the meteorite impact is distinct from the sonic boom generated by the meteoroid in flight (Edwards, Eaton, & Brown, 2008). Because seismic waves from both the impact and the sonic boom might be recorded within a short period of time and because the waves from the sonic boom may arrive before, after or during the impact waves, it has proven challenging to use seismic records as a means for meteorite location (Jeremy Tatum, personal communication).

Volcanic eruption (tremor)

Seismic events preceding a volcanic eruption are recorded as earthquakes and, unsurprisingly, look like crustal earthquakes, but can serve as a valuable predictor of volcanic activity, particularly if the events become shallower over time. With continued study, these events might be relabelled as “*volcanic eruption*”. Additionally valuable for discrimination is that volcanic activity has a much higher b-value (≅2) than regular tectonic seismicity (≅1) (Cassidy, et al., 2011). As volcanic events often occur in a swarm, it is possible to determine an approximate b-value with only a few weeks’ recordings.

As an example, in 2007 an unusual, intense sequence of earthquakes was recorded 20 km west of the Nazko cone in British Columbia, the most recent (~7200 ya) volcanic center within the Anahim volcanic belt and an area which had previously been seismically inactive (Cassidy, et al., 2011). Within a three week period, more than 800 earthquakes were located at a depths of 25 - 31 km (in the lower crust) and within a radius of about 5 km. The clear P- and S-wave arrivals indicated that these were high-frequency (volcanic-tectonic) earthquakes with a b value of 1.9 – anomalously high for crustal earthquakes but consistent with volcanic-related events. While neither harmonic tremor nor long-period events were observed, some spasmodic bursts were recorded and co-located with the earthquakes’ hypocenters. These observations were similar to those of an earthquake sequence deep beneath Lake Tahoe, California, in 2003 – 2004; the Nazko sequence was therefore interpreted as an indication of an injection of magma into the lower crust, which typically produces high-frequency, volcanic-tectonic earthquakes and spasmodic bursts.

Hydroacoustic event

A hydroacoustic event is a seismic event that occurs in water, typically an explosion or an implosion. Airgun shots as part of offshore hydrophone surveys can produce seismic arrivals at land-based seismograph stations. For example, the R/V Langseth, as part of the CLOCKS experiment to map the Queen Charlotte Fault, produced hundreds of apparently M_L 1–2 events recorded at the CNSN stations on Haida Gwaii in July of 2021. Underwater implosions can also produce clear recordings at land-based seismograph stations. For example, it was possible to infer the time and location of the implosion of the submarine Kursk from seismic records (Koper, Wallace, Taylor, & Hartse, 2006).

Not existing

The NEDB eqtype “Z” denotes “ghost” events, that is, events which at some point were suspected as real seismic events, but which upon further investigation were determined not to be. It is better to retain these fictitious events and classify them as “*known not existing*” than to simply delete them, because it can help to prevent their reintroduction as real events at a later date. For example, misinterpretations and typographical errors in historical texts resulted, for a while, in the cataloguing of some fictitious 17th century earthquakes (Stevens, 1995). In contrast, an earthquake was for some time believed to have occurred between Jacques Cartier’s first (1534) and second (1535) voyages near Charlevoix, Quebec. Upon review, it was known only to be prior to 1637 and reported felt only in Ontario (Gouin, 1994). This event is best classified as a “*suspected earthquake*” with poorly constrained date and location.

Not reported (null)

This event type is useful for data originating from agencies and/or schemas that lack event type information. An example is NEDB eqtype “S”, denoting “single or two stations locations”. This coding tells us that the analyst was uncertain about the quality of the epicentre, but nothing about the processes that gave rise to the seismic event, not even a hint as to whether it was anthropogenic or tectonic. Events coded as eqtype “S” must therefore be interpreted as having an event type *“not reported*” or null (unset). Fortunately, in the case of the NEDB, an event type can be inferred from the comments for the event in the majority of cases, but since the epicentre is poorly constrained, the event type certainty can only be “*suspected”*.

The single-letter code for “*not reported*” is the space character, ASCII 32.

Appendix B: Current areas of interest for fluid injection induced events

Since northeastern British Columbia and northwestern Alberta have historically exhibited low rates of natural seismicity (Figure 4), contemporary events are, therefore, likely to be induced by industrial activity in the region (Atkinson, et al., 2016).

The GSC and British Columbia Oil and Gas Commission (BGOGC) have partnered to study seismic activity in the Horn River basin in northeastern BC (see Figure 5), where considerable hydraulic fracturing is taking place (BCOGC, 2012; Farahbod, Kao, Walker, & Cassidy, 2015; Larochelle, Liu, & Kao, 2016). Similar studies are being conducted in Alberta by the Alberta Geological Survey with assistance from the University of Alberta and University of Calgary (Schultz, et al., 2020).

Identifying "*fluid injection*" induced events related to wastewater disposal by their location is relatively simple as disposal wells are usually long-term features, although this does require up-

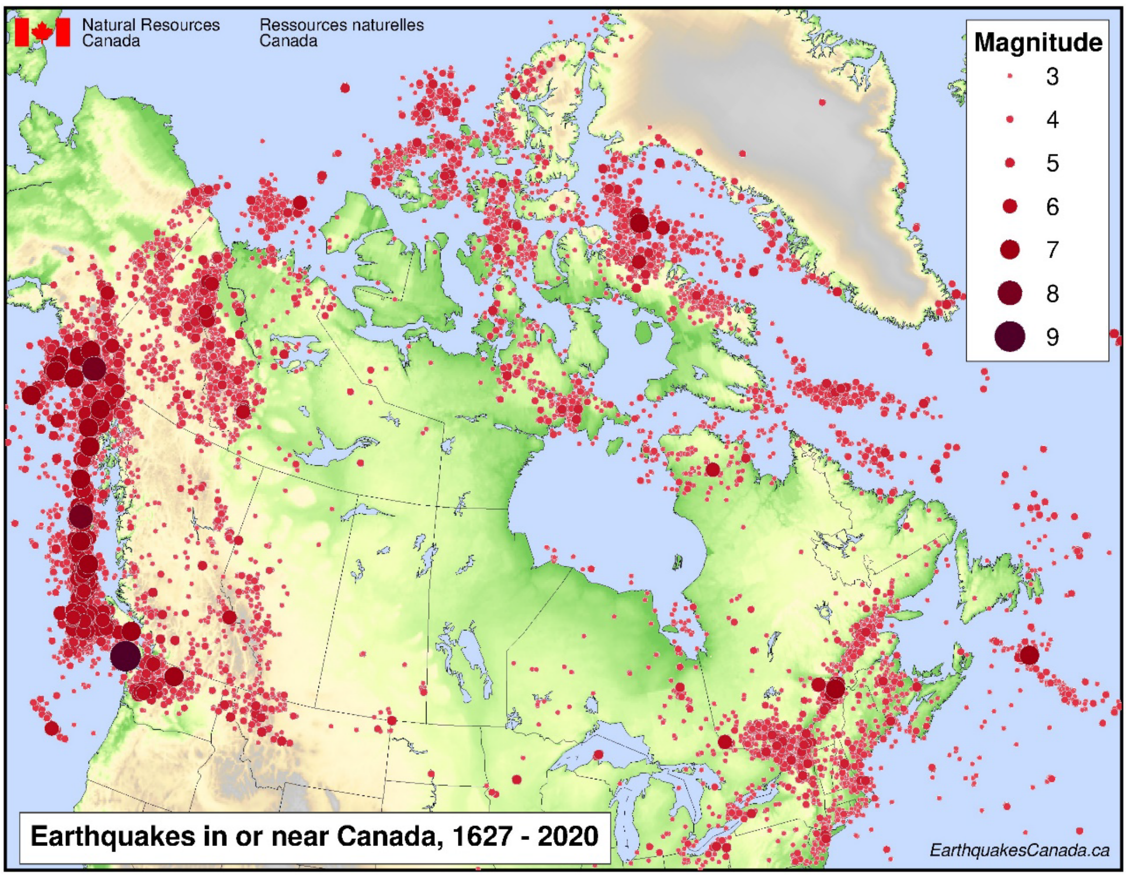

Figure 4: Map showing historical earthquake database for Canada. The events are from the Seismic Hazard Earthquake Epicentre File for events up to 2020 (SHEEF2020, in preparation). This is an extension of SHEEF2010 which was used in the fifth generation seismic hazard maps for Canada (Halchuk, Allen, Rogers, & Adams, 2015). Before being used in hazard calculations, some events shown in northeastern British Columbia and western Alberta are routinely removed from the catalogue using purely geographical criteria, because they are suspected or known to be induced by oil & gas production activities.

to-date knowledge of active disposal wells (BCOGC, 2019). Identifying events related to hydraulic fracturing is more problematic because the activity is less static, with frequently changing location and intensity (Schultz, et al., 2020). However, a sudden increase of seismic activity in an area where there has been none in the past strongly suggests that newly observed events are likely induced. For events induced by hydraulic fracturing or wastewater disposal, an additional challenge is that while fluid injection occurs over an extended period, the associated induced earthquakes may occur at some point during this period or later (Farahbod, Kao, Walker, & Cassidy, 2015).

Figure 5 shows the current areas of interest for fluid injection induced events in Canada (regions with historically low seismicity and large-scale fluid injection activities). These are the Horn River Basin, Liard Basin, and the Montney Play in British Columbia, the Duvernay Play (Fox Creek, Rocky Mountain House, Brazeau, Cordel and Crooked Lake) and Basal Banff/Exshaw Formation (Cardston) in Alberta, and Norman Wells in the Northwest Territories. Earthquakes shown in Figure 5 were catalogued prior to the adoption of QuakeML event types, when events were only catalogued as “Induced” if they were known to be industry-related. Many of the earthquakes shown in these areas of interest regions can be reclassified, by the procedure defined in the main body of this document, as “*suspected fluid injection*” induced events.

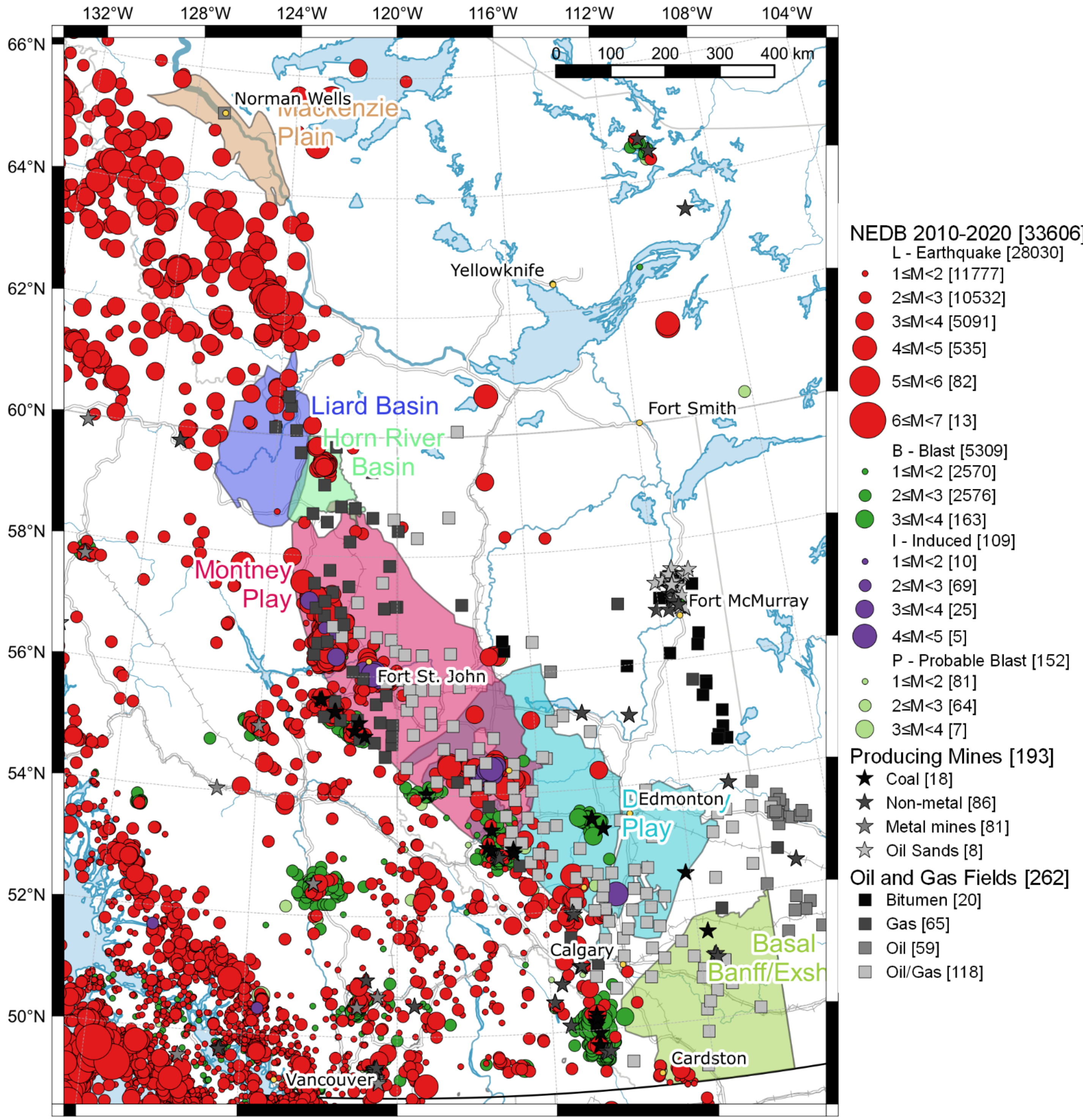

Figure 5: Areas of current interest for fluid injection induced and triggered events in Canada. Circles are seismic events are from the NEDB, 2010–2020, coloured by event type. Stars and squares are producing mines and oil and gas fields with production in 2020 and 2019, respectively (LMS; CER, 2021). Shaded areas are unconventional gas plays: Mackenzie Plain (NTGS, 2017), Liard Basin (NTGS, 2018), Horn River Basin (BCOGC, 2014), Montney Play (Schultz, et al., 2020), Duvernay Play and Basal Banff/Exshaw (Rokosh, et al., 2012).

Appendix C: Current areas of interest for reservoir loading induced events

As of 2018, reservoir-triggered seismicity has been identified near at least six reservoirs in Canada, all in the province of Quebec. Reservoir-triggered seismicity is thought to be controlled by the height of the impounded water, however many of the largest dams in Canada have not generated seismicity, including Manic-5 in Quebec. Despite the presence of large dams, no reservoir-triggered seismicity is known to have occurred in British Columbia or Alberta (Lamontagne, Rogers, Cassidy, Tournier, & Lawrence, 2018)

Table 4 lists significant recent and planned reservoir impoundments in Canada. Between 2012 and 2022, the only reservoirs to be impounded with dams taller than 50 m are associated with the La Romaine complex in Quebec. Some reservoir loading induced events have been recorded near Romaine-2.

Table 4: Significant recent and planned reservoir impoundments in Canada. (Ministère de l'Environnement du Québec, 2001; Hydro-Québec, 2003; Hydro-Québec, 2004; Hydro-Québec, 2007; BC Hydro, 2010; SNC Lavelin, 2011; Keeyask Hydropower, 2012) Note that Eastmain-1-A augmented an existing generating station commissioned in 2006 with little change in the height of impounded water and Site C has not been approved.

Generating Station	Latitude [°N]	Longitude [°E]	Watershed	Province	Dam Height [m]	Impound-ment
Toulnustouc	49.9641	-68.1321	Manicouagan	Québec	77	2005
Eastmain-1	52.176	-76.024	La Grande	Québec	30	2006
Péribonka	49.508	-71.183	Péribonka	Québec	80	2007-2008
Eastmain-1-A	52.180	-76.035	La Grande	Québec	30	2011-2012
Romaine-2	50.624	-63.194	Romaine	Québec	121	2014
Romaine-1	50.385	-63.261	Romaine	Québec	38	2015-2016
Romaine-3	51.114	-63.400	Romaine	Québec	92	2017
Muskrat Falls	53.246	-60.773	Churchill (lower)	Newfoundland and Labrador	34	2019
Romaine-4	51.348	-63.487	Romaine	Québec	87	2020
Keeyask	56.3465	-95.2048	Nelson	Manitoba	28	2020-2022
Site C	56.195	-120.914	Peace	British Columbia	60	2024

Appendix D: Implementation Notes

In this section, the implementation in various relevant databases is discussed, as well as translations between them.

Official Languages

Information that is shared with the general public about seismic events, whether via the media or via the EarthquakesCanada and SeismesCanada web pages (see Internet Sources) must be made available in Canada's two official languages, English and French.

Table 5 summarizes the English and French equivalents for the most common event types for duty seismologists and website developers.

Figure 6 is a diagram showing the first phase of event type discrimination schematically, the equivalent of Figure 2, but in French.

Table 5: Common QuakeML event types and certainties in both official languages.
This accounts for the vast majority of the events in the NEDB.

Event type	Type d'évènement
earthquake	séisme
mining explosion or quarry blast	explosion minière ou dynamitage de carrière
industrial explosion or road cut	explosion industrielle ou travaux routiers
controlled explosion	explosion contrôlée
mining-induced	évènement minier
reservoir loading	mise en eau de réservoir (induit)
fluid injection	injection de fluide (induit)
induced or triggered event	évènement lié à l'industrie (induit)

Event type certainty	Certitude de type d'événement
known	connu/connue
suspected	soupçonné/soupçonnée

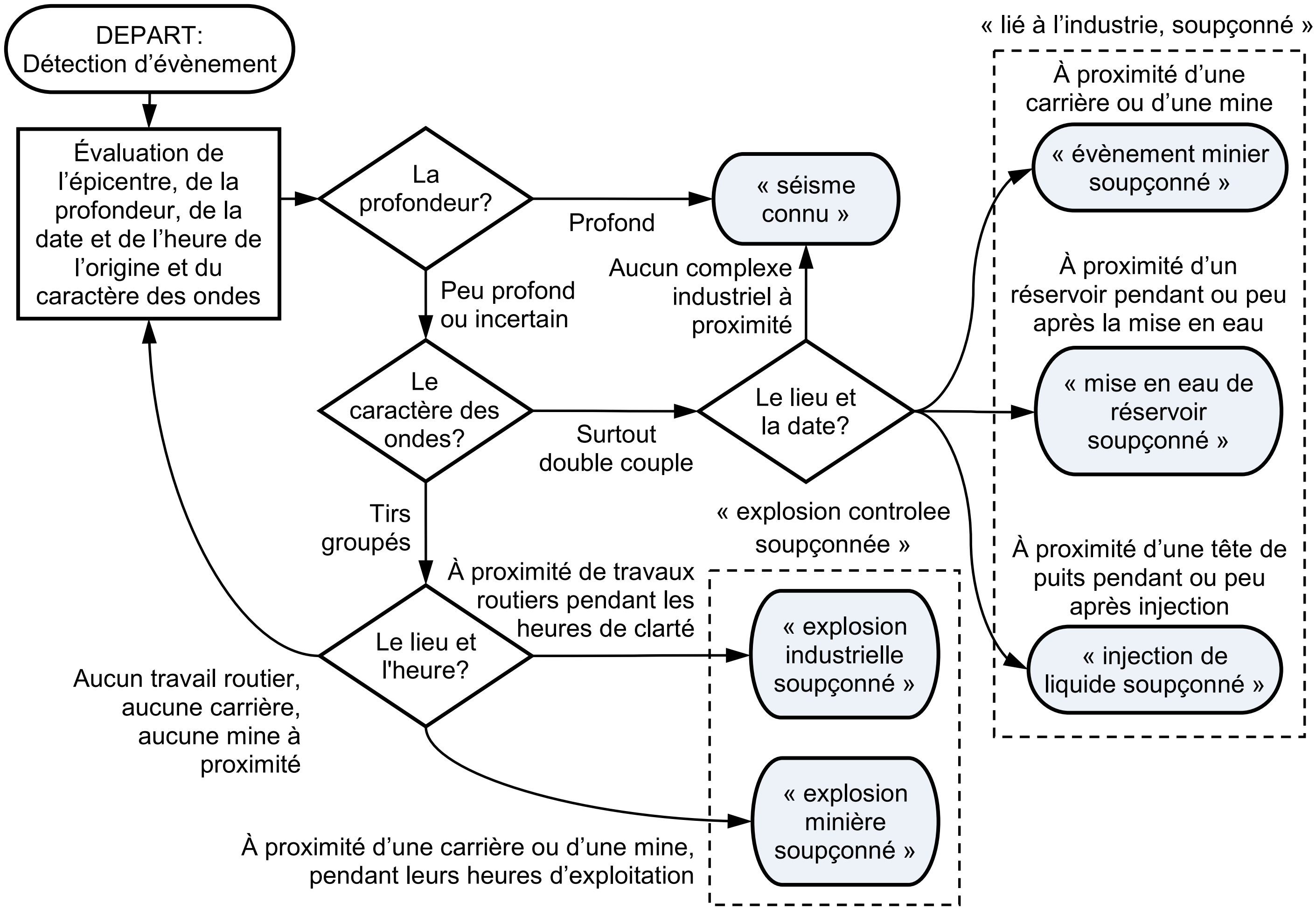

Figure 6: La détermination du type d'événement le plus probable. Ce logigramme représente la discrimination routinière du type d'événement de la grande majorité des événements dans le NEDB. Les techniques utilisées pour évaluer la profondeur, le caractère des ondes et la proximité spatiotemporelle sont expliqués ailleurs dans ce document. Notez que pour les événements qui ne sont ni manifestement profonds ni principalement double couple, qui ressemblent aux tirs groupes, et qui ne peuvent pas être associés à une installation industrielle, il existe une boucle qui indique que le caractère des ondes et l'hypocentre doivent être réévalués. Il est difficile d'évaluer le mécanisme et la profondeur pour les événements qui sont petits et/ou éloignés des régions densément instrumentées du réseau sismographe. Dans ces cas, plusieurs branches du logigramme peuvent être parcourues avant de trouver une hypothèse qui correspond aux données. Les types d'événements plus rares ne sont pris en considération qu'après plusieurs itérations de cette procédure. La deuxième phase de la procédure, la confirmation du type d'événement (la transition de « soupçonné » a « connu »), a des critères qui depend du type d'événement, par exemple une mine peuvent confirmer événement minier.

NEDB Schema

The NEDB “eq” database schema was developed over time in response to the needs of CHIS. The schema (and associated NPF “pickfile” format) defines a four-character “eqtype” field. Prior to the adoption of QuakeML event types, the “eqtype” field captured event type and certainty together in a single-letter code. With the adoption of the QuakeML event types, it becomes possible to capture many more event types.

In order to maintain uniformity and minimize ambiguity it proposed that the “eqtype” field should be reprocessed for all events (both before and after the adoption of this procedure). New coding

Table 6: Recommended re-encoding of NEDB “eqtype”. This is intended only for events catalogued prior to adoption of QuakeML event types. Leftmost "from" column is original usage. Rightmost columns indicate proposed re-encoding. Where differences existed in the original usage between the east (agency code GSC) and in the west (agency code PGC, for Pacific Geoscience Centre), this is indicated.

Old	New	Old Definition	New Classification Notes
L _ _ _	L _ k e	Local earthquake	“*known earthquake*”
T _ _ _	T _ k e	Teleseismic earthquake	“*known earthquake*”
S _ _ _	S _ s _	Single or two-station location	Initially “*suspected not reported*” but sub-types can be further distinguished by inspecting comments (still “*suspected*”). See note 4 below.
B _ _ _	B _ k x	Blast	Initially super-category “*explosion*” but sub-types can be further distinguished by inspecting comments. See note 3 below.
P _ _ _	P _ s x	Possible blast	See Blast
R _ _ _	R _ k r R _ k e	Rockburst Earthquake in a bordering region	“*known rock burst*” (east of 110°W) “*known earthquake*” (west of 110°W, prior to 2021)
U _ _ _	U _ s r	Unconfirmed rockburst	“*suspected rock burst*”
I _ _ _	I _ s i	Induced	Initially “*suspected induced or triggered event*” but sub-types can be further distinguished geographically (still “*suspected*”). See note 2 below.
X _ _ _	X _ k j	Controlled explosion	“*known experimental explosion*”
G _ _ _	G _ k u	“Ghost” event	“*known not existing*”

Notes to Table 6:

1. Isolated events prior to the date of adoption of the current procedure will have their event type coding corrected, e.g. the 1965 Hope landslide as L _ k l and the 1998 Swissair crash as B _ k p .
2. Events in the super-category “*suspected induced or triggered event*”, I _ s i, will be reclassified when they clearly fall into a specific sub-category. Induced events in Canada east of 80°W prior to the adoption of this procedure are specifically “*suspected reservoir loading*” induced, thus I _ s w, while induced events in Canada west of 100°W prior to adoption of QuakeML event types are specifically “*suspected fluid injection*” induced, thus I _ s k.
3. Events in the super-category “*explosion*”, B _ k x or P _ s x, will be reclassified when they unambiguously fall into a specific sub-category according to the original analyst’s comments. For example, events categorized as B _ k x which are identified as blasts in the comments will be reclassified as “*known mining explosion*” B _ k m. Similarly, events may be reclassified as “*industrial explosion*” B _ k d or P _ s d when the comments indicate that the event was clearly related to road construction.
4. After initial conversion of single or two-station location events to “*not reported*” S_ s _ events, comments will be inspected to determine most likely event type, with the certainty left as “*suspected*”. The coding will then become one of: “*earthquake*” S _ s e, “*rock burst*” S _ s r, “*mining explosion*” S _ s m or “*industrial explosion*” S _ s d.

is distinguished from old coding both by case and by letter position. The first character is the old event type, the third character is the event type certainty and the fourth character is the new event type. Given that there are differences in how meaning is assigned to the old single character codes (in the east and the west as well as over time), the preservation of old coding may serve to resolve ambiguities. Where there is disagreement between the old single letter uppercase code and the new two-letter lowercase code, the new code should take precedence.

The conversion of the NEDB to the new coding scheme consists of three steps. In a first bulk reclassification, old codes are mapped to new codes as indicated in Table 6. In a second step, events in certain super-categories are sorted into sub-categories based on information already in the database, such as geographic location or the contents of comments fields. Finally, information outside the database is incorporated, for example to record confirmation of "*suspected fluid injection*" induced events by reclassifying them as "*known fluid injection*".

Once the new procedure for event type discrimination and coding has been adopted, only the third and fourth characters of the "eqtype" field should be filled in, corresponding to the event type certainty and event type, respectively.

Antelope CSS3.0 Schema

Antelope implements an extension of the CSS3.0 schema (Anderson, Farrell, Garcia, Given, & Swanger, 1990).

If necessary, the two characters of the existing "etype" field in the "origin" table be used to code event type certainty (first character) and event type (second character). This replaces the default two-letter codes which define event type only, and which do not overlap with the new proposed coding because none of them begins with "s" or "k".

LOON Data Format

The LOON data format supports only a single character for event type, so it will not be able to support the two-letter coding schema. It will have to be changed or abandoned in order for event types such as "suspected fluid injection induced or triggered" to be used.