

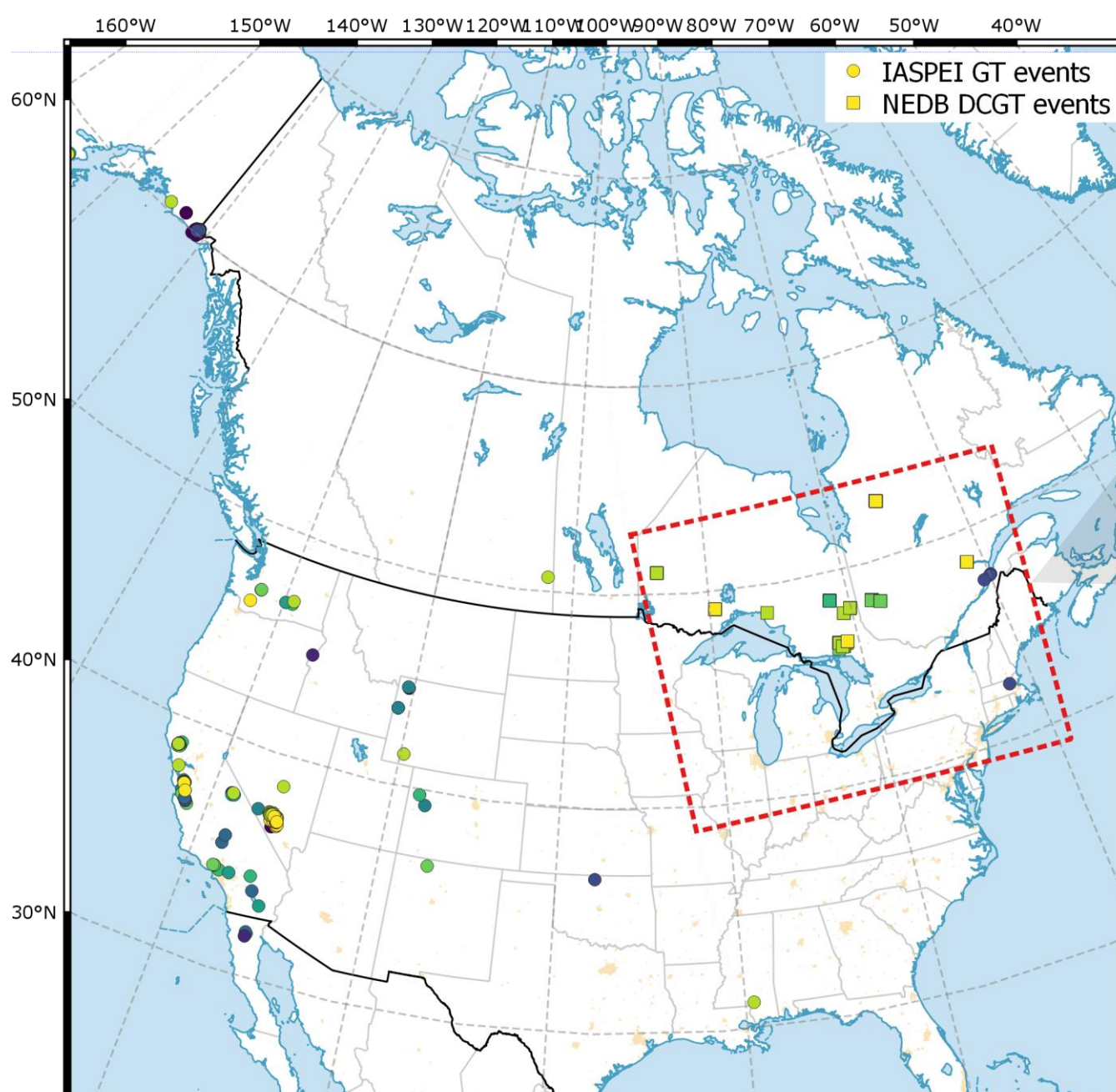


## Abstract

Depth estimation is an important part of discriminating anthropogenic from non-anthropogenic events. For small events in sparsely instrumented regions, there are few methods available for depth estimation. Ground-truth (GT) events at shallow depths will be a key part of any scheme to validate new methods. Although the IASPEI GT catalog contains more than a thousand events with 1 km < depth < 5 km, only a handful are in eastern North America. Rock bursts and other mining-related events in underground mines can be considered shallow depth-constrained ground truth (DCGT) events when the depth has been confirmed by direct observation. At the Canadian Hazards Information Service (CHIS), we have good working relationships with many mine operators. In mid-2016, we began requesting depth information when confirming events. Up to present, we have assembled a catalogue of DCGT blasts and mining-related events that includes 200 events with moment magnitude  $1.5 \leq M_W < 2.5$  and 28 events with  $2.5 \leq M_W \leq 3.3$ . These events form nine clusters, spanning 1600 km across Ontario and Quebec. We explore this catalogue, and present a preliminary evaluation of the accuracy of depths obtained by regional depth phase modeling (RDPM).

## Introduction

Ground truth seismic events have accurately known coordinates. Such events facilitate the development of improved velocity models, techniques for event location and means of event type discrimination. The IASPEI GT (ISC, 2008) reference events include regional and teleseismic explosions and earthquakes with epicentral uncertainty 0-5 km with 95% confidence (GT0 to GT5). This catalogue is mainly concerned with accurate epicenters: "GT-1-2 events are assumed to be shallow, but depth is unknown." (Bondár & McLaughlin, 2009).



Map 1 shows shallow (depth 0.1-4.9 km) IASPEI GT events in North America. There are just 5 events east of 100°W: these events are widely dispersed and they have a narrow range of depths (3.6-3.9 km).

The depth of a seismic event is an important indicator of its genesis; if it is deeper than 5-10 km, then it is not anthropogenic.

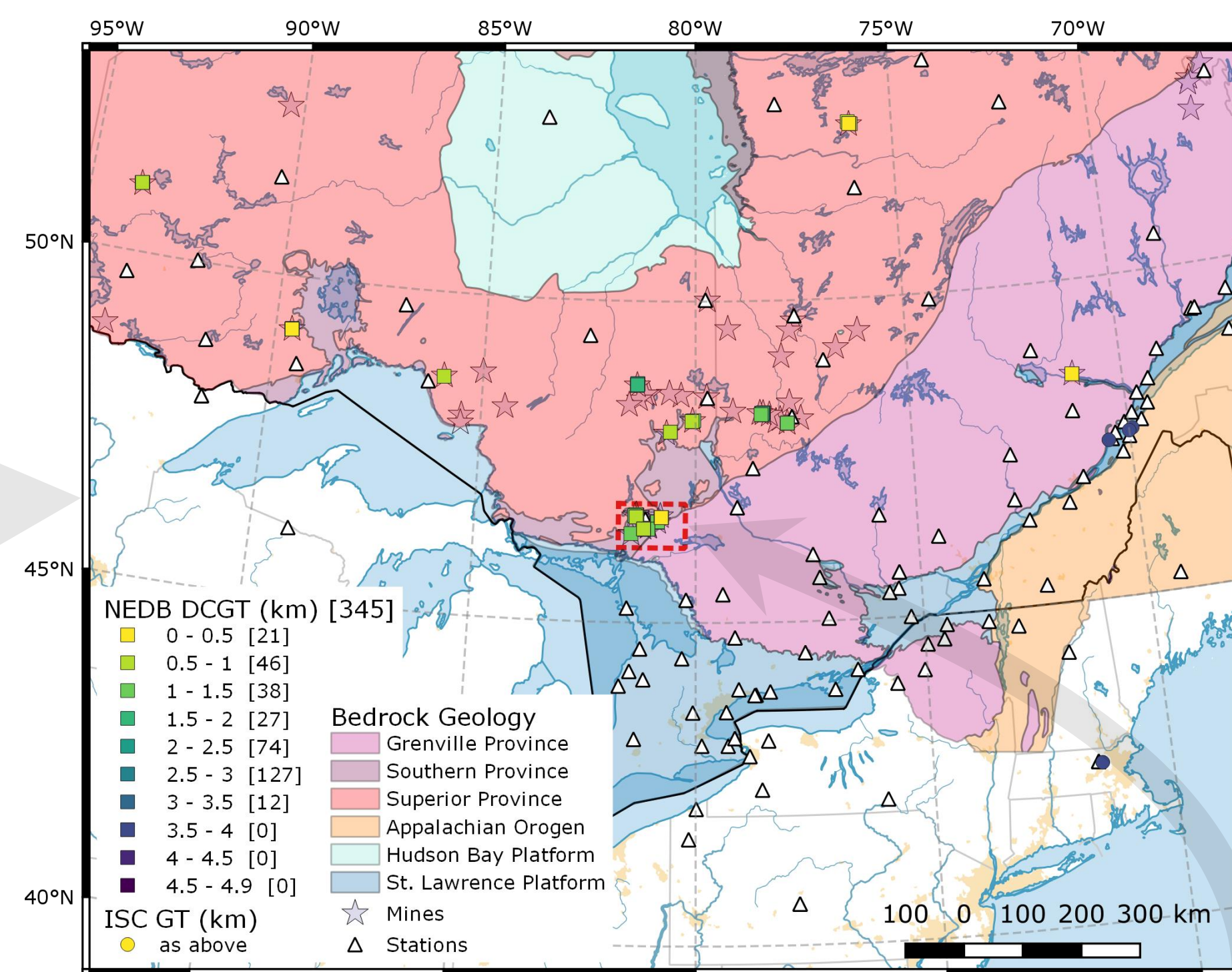
In most of the world, station spacing does not permit depth estimation of shallow events from direct phases. For events smaller than magnitude 4, depth estimation using teleseismic depth phases is not possible. RDPM (Ma, 2010) was developed in conjunction with CHIS seismologists, and has been in routine use at CHIS since 2006, but in its current form is time consuming and depends on correct phase identification.

Methods of estimating depth from crustal Rayleigh wave (Rg) amplitudes have been proposed but have not been proven transportable between regions. An obstacle to the development and validation of new methods for shallow events is the lack of ground truth.

## Mining-Related DCGT Events

Since 2016, some mine operators in eastern Canada have been providing CHIS with confirmed depths upon request, for events in their mines. The epicentre for these events can be considered GT1 or GT2 but the depth is "GT0.01" because the depth is confirmed by physical observation to within approximately 10 m (below surface).

To date, we have catalogued 345 DCGT events from nine mining districts in eastern Canada. The events are all located in shield provinces (see Map 2).



Map 2: DCGT events in eastern Canada. Bedrock geology and underground producing mines are from the Atlas of Canada.

Figure 1 shows that the events range in depth from 0.06 to 3.20 km and in moment magnitude from 0.3 to 3.3  $M_W$ .

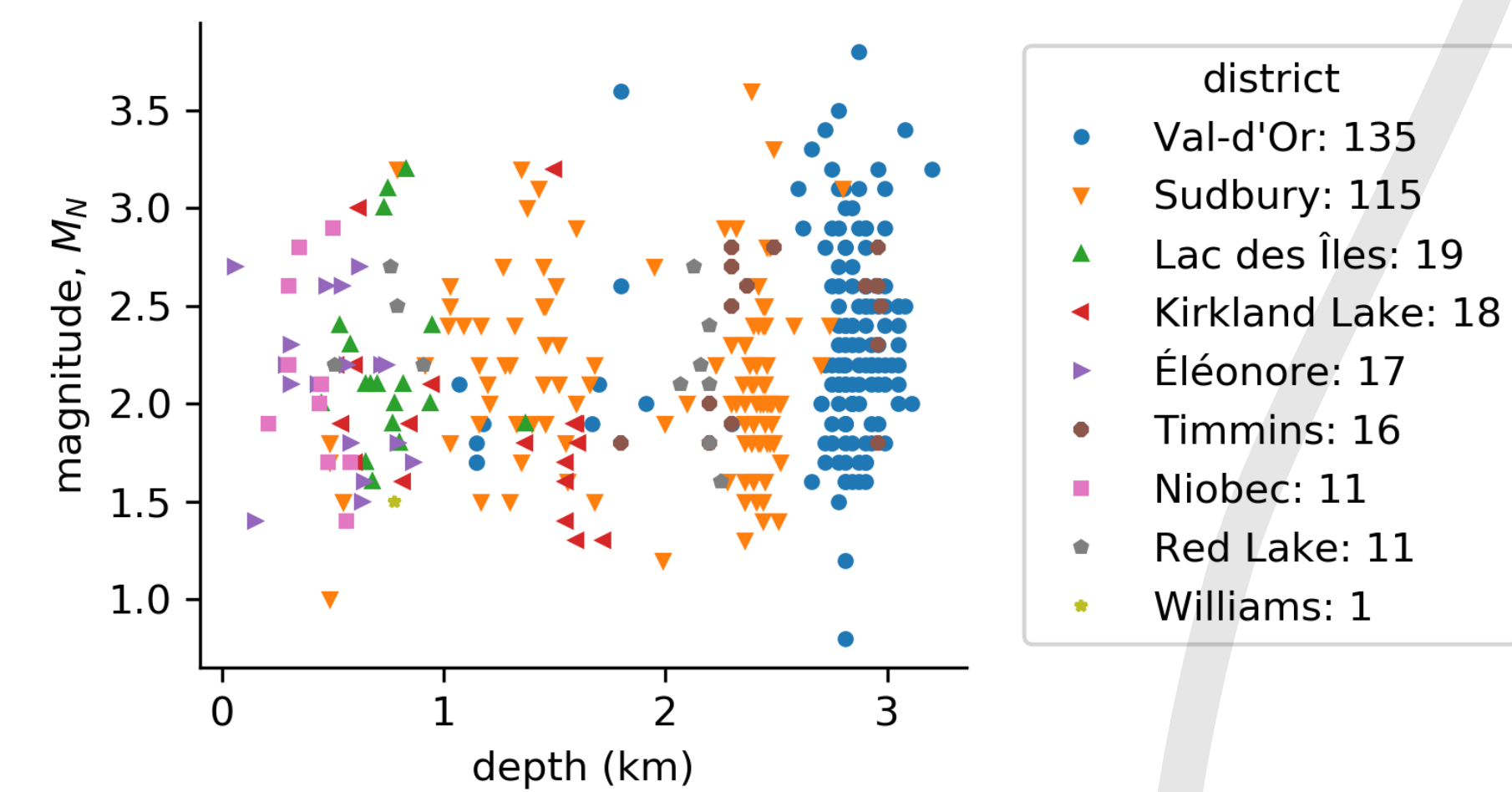
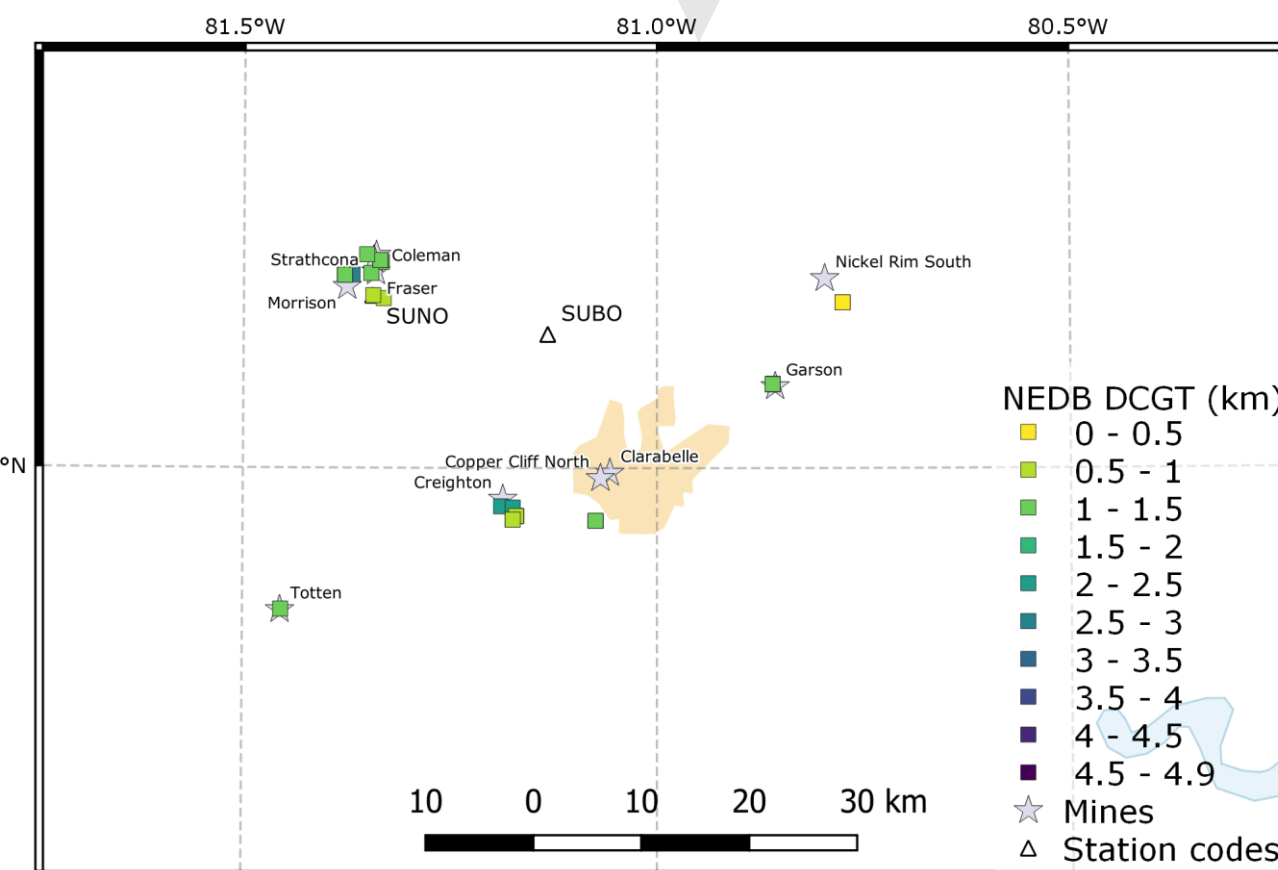


Figure 1: Depths and magnitudes of DCGT events in eastern Canada. The Nuttli magnitude,  $M_W$  can be converted to an approximate moment magnitude using  $M_W \approx M_N - 0.5$  (Bent et al., 2014). The number of events in each mining district is indicated in the legend.

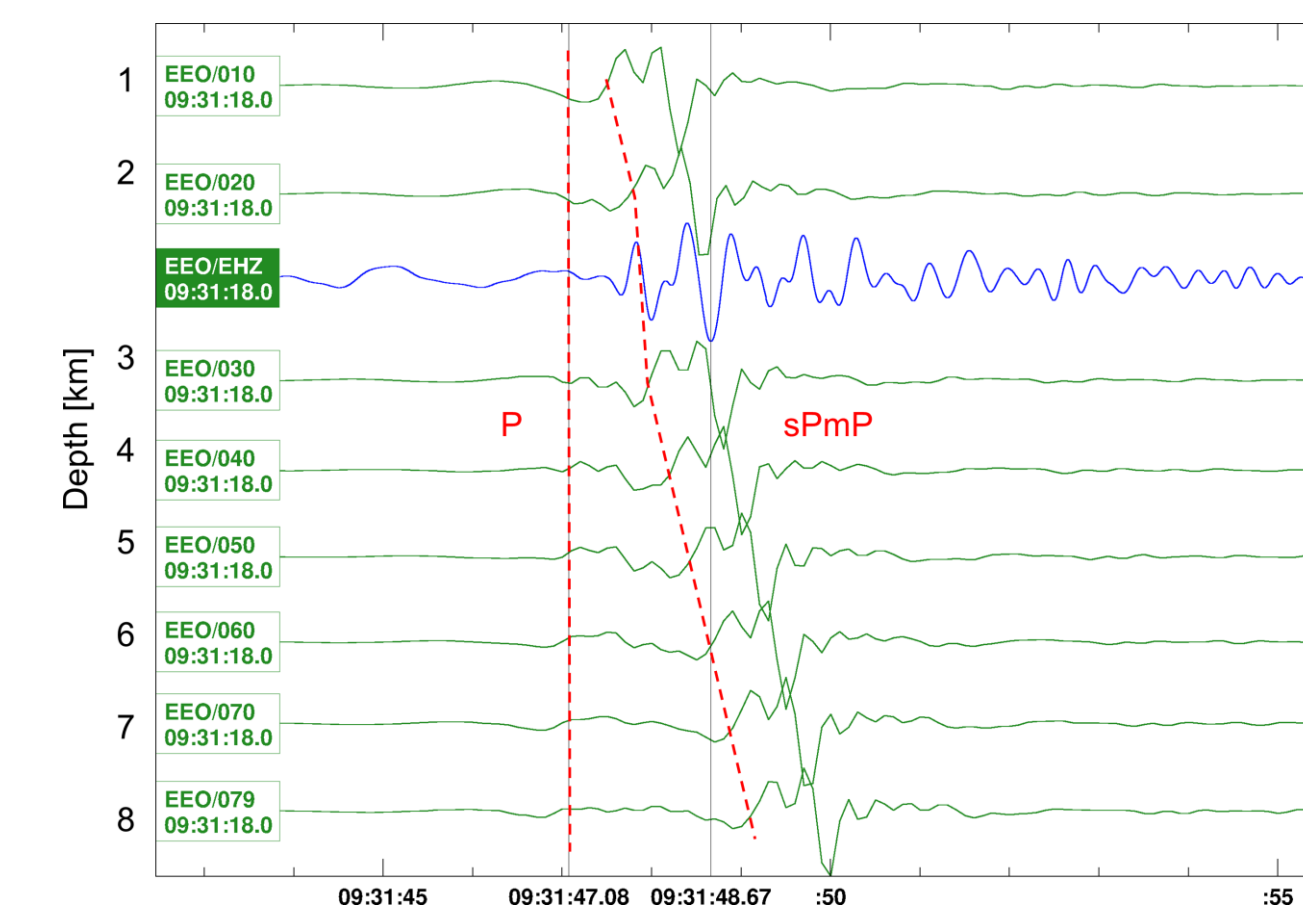
The mining district of Sudbury provides a particularly rich subset of data, with DCGT events spanning 0.5-3 km in a 50 km wide cluster (Map 3). With 8-10 stations between 150 and 250 km away, it becomes possible to control for the effect of azimuth on regional depth estimates.



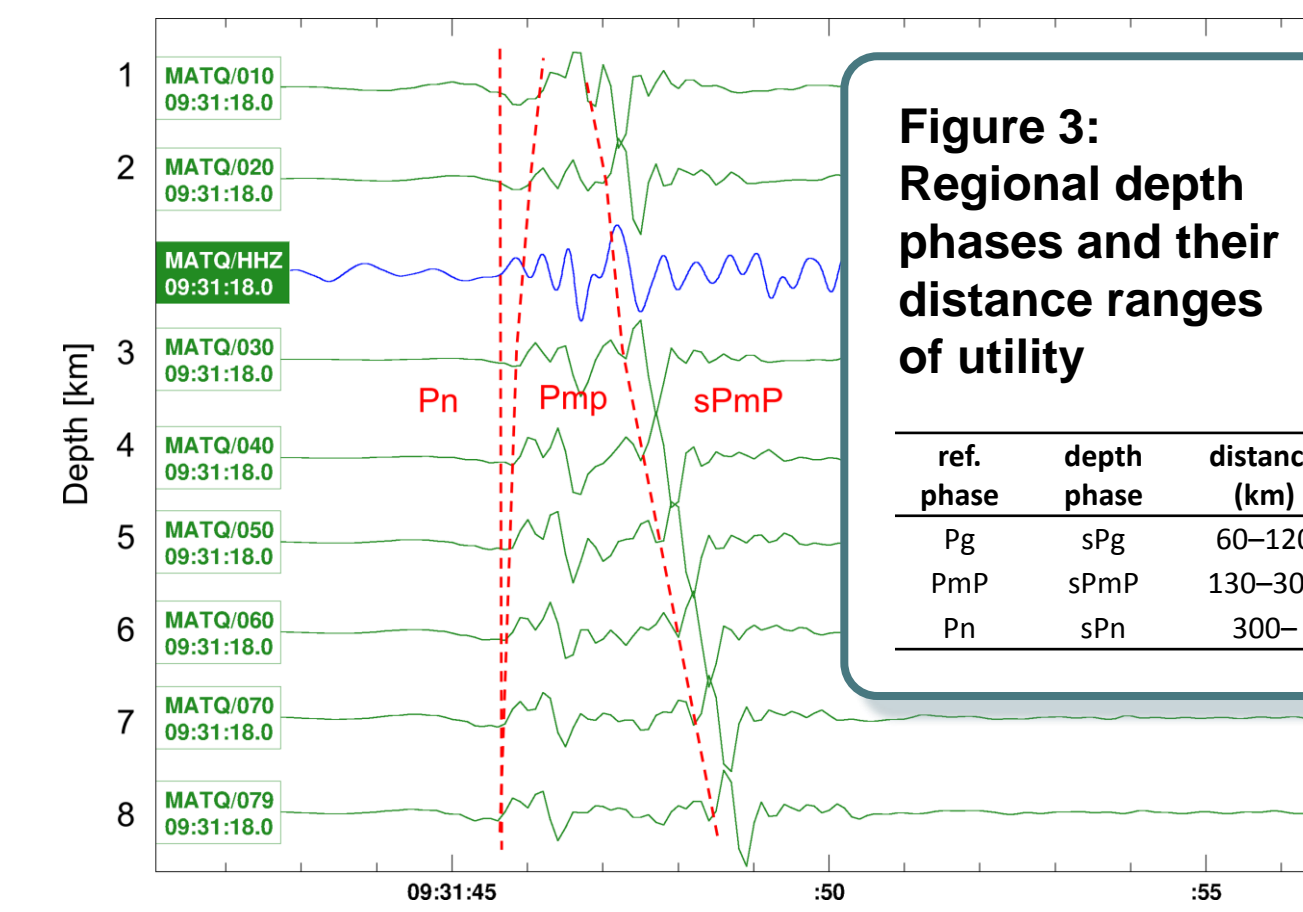
Map 3: DCGT events in the Sudbury mining district.

## Regional Depth Phase Modeling

Since 2006, RDPM has been used routinely to estimate the depths for events in eastern Canada. Typically, only events above  $M_N \geq 3.0$  have sufficient signal-to-noise ratio (SNR) to permit identification of regional depth phases. Figure 2 shows an example of an RDPM analysis of a 3.1  $M_N$  DCGT event.



a) Waveforms at station EEO, 185 km from epicentre, filtered using 0.5-3.5 Hz 6th order bandpass. Best fit depth 2.5 km.



b) Waveforms at station MATQ, 178 km from epicentre, filtered using 0.7-3.5 Hz 6th order bandpass. Best fit depth 2.5 km.

Figure 3: Regional depth phases and their distance ranges of utility

ref. phase	depth (km)	distance (km)
Pg	sPg	60-120
PmP	sPmP	130-300
Pn	sPn	300-

Figure 2: RDPM for 3.1  $M_N$  mining-induced event near Val d'Or. Synthetic waveforms are in green; observed waveforms are in blue. Arrivals of labelled phases in synthetic waveforms are shown as dashed red lines, and approximate. Origin time was 2016-07-24 09:31:19 UTC. Average of two depth estimates is 2.5 km below surface. Confirmed depth 2.87 km below surface.

RDPM is labour-intensive, requiring careful selection of filters and identification of phases (see Figures 2-3). It gives depths consistent with estimates based on Rg modeling and Rg/Sg spectral ratios for shallow events (Ma & Motezadian, 2012), and based on direct phases for deeper events (Ma, 2010), but it has not been tested against a catalogue of DCGT events.

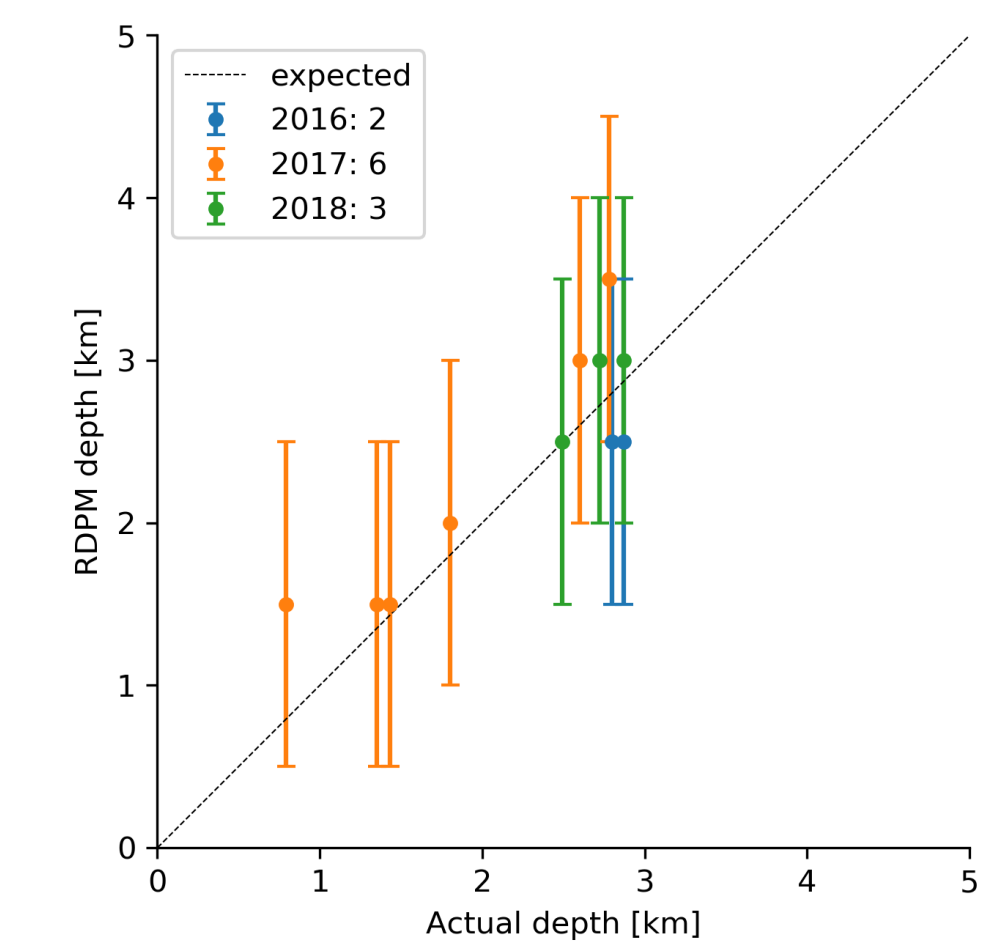
## RDPM Validation

To date, a total of eleven DCGT events in Sudbury and Val d'Or have had depths estimated using RDPM. In Figure 4a, these events are plotted with a nominal  $\pm 1$  km uncertainty assigned to the RDPM estimates. Figure 4b shows the distribution of depth residuals.

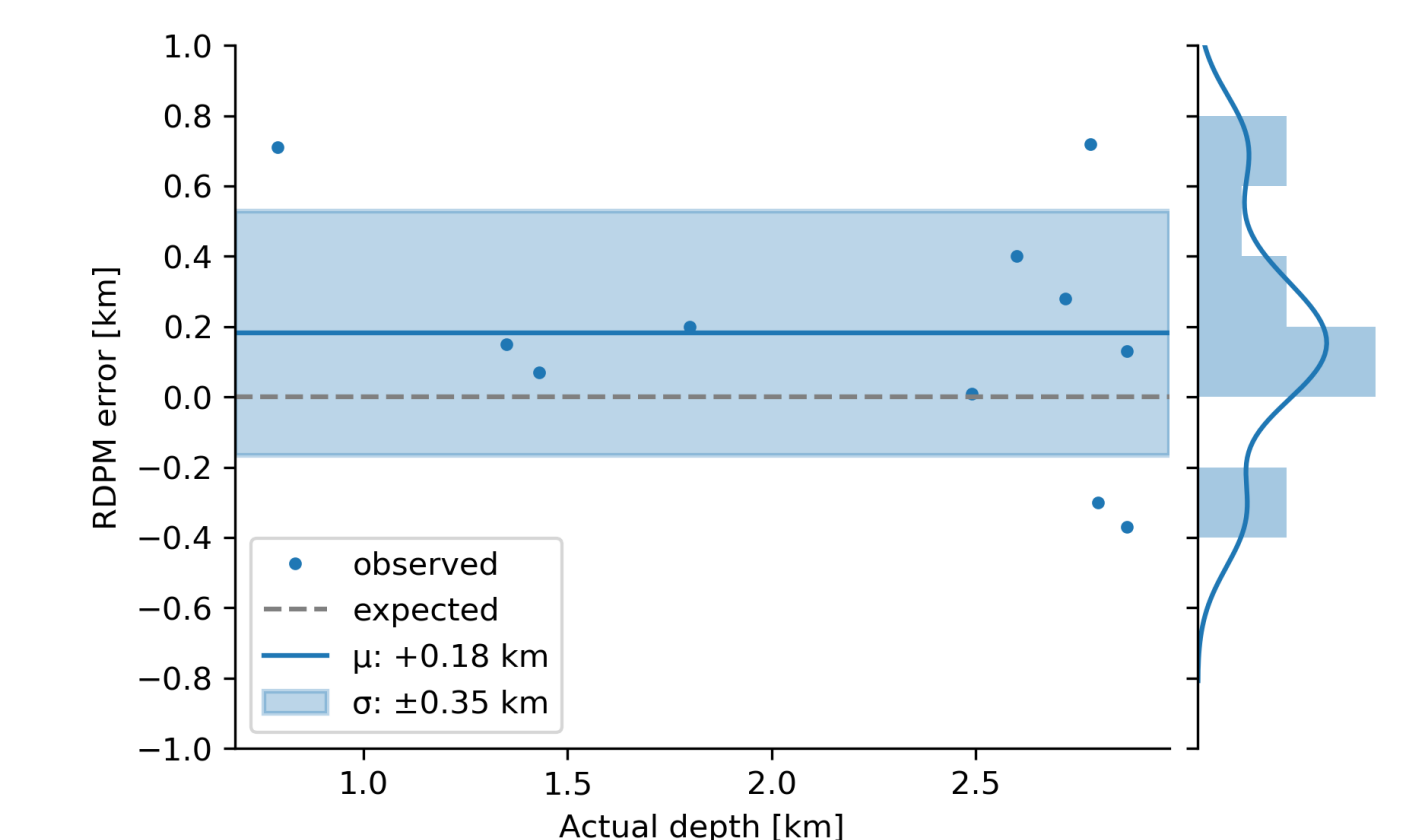
The RDPM estimates are on average  $\mu=0.18$  km too deep, with a standard deviation of  $\sigma=0.35$  km. The dataset is too small to judge whether there are systematic trends in the data or to place bounds on the frequency of extreme outliers. Although the uncertainty could be expressed as  $\pm 0.7$  km with 95% confidence ( $\pm 2\sigma$ ), the nominal  $\pm 1$  km is a more conservative expression of the expected range of errors.

The RDPM technique has reasonable accuracy, but is limited in utility to larger events and is time consuming because, in its current form, it requires significant effort and judgment on the part of the analyst.

## RDPM Validation (continued)



a) RDPM depth estimates with nominal  $\pm 1$  km uncertainty. No error bars are shown on actual depth, because, at  $\pm 0.01$  km, they would not be visible.



b) Error in RDPM depth estimates. The mean error  $\mu$  and the standard deviation  $\sigma$  are indicated in the legend. Right panel shows bin counts and a kernel density estimate.

Figure 4: Comparison of RDPM depth estimates to confirmed "ground truth" depths of mining events. To date, eleven DCGT events have been processed using RDPM and found to have sufficient signal-to-noise ratio to permit depth estimation.

## Conclusion

We present a preliminary catalogue of shallow DCGT events from eastern Canada, starting in 2016. As it grows, the data will continue to be incorporated in the Canadian National Earthquake Database (CHIS, 2019). The dataset includes events from nine mining districts in eastern Canada and samples a wide range of magnitudes and depths. We demonstrate the utility of our DCGT catalogue by investigating the accuracy of RDPM depth estimates.

Rapid and accurate depth estimation techniques are important tools for discrimination of anthropogenic and natural events. We expect this catalogue to contribute to the development and validation of estimation of the depths of seismic events.

## References

Ackerley, N., Peci, V., Adams, J., & Halchuk, S. (in press). Seismic Activity in the Northern Ontario Portion of the Canadian Shield: Annual Progress Report for the Period January 1 - December 31, 2017. Toronto: Nuclear Waste Management Organization.

Bent, A., & Greene, H. (2014). Toward an Improved Understanding of the MN-Mw Time Dependence in Eastern Canada. *Bull. Seism. Soc. Am.*, 104(4), 2125-2132.

Bondár, I., & McLaughlin, K. L. (2009). A new ground truth data set for seismic studies. *Seism. Res. Lett.*, 80(3), 465-472.

CHIS (2019) National Earthquake Database. Ottawa, Canada: Canadian Hazards Information Service. <http://earthquakescanada.ca/stndon/NEDB-BNDS/bulletin-en.php>

ISC (2008) IASPEI GT reference events. Thatcham, United Kingdom: International Seismological Centre. <http://www.isc.ac.uk/gtevents/search>

Ma, S. (2010). Focal depth determination for moderate and small earthquakes by modeling regional depth phases sPg, sPmP, and sPn. *Bull. Seism. Soc. Am.*, 100(3), 1073-1088.

Ma, S., & Motezadian, D. (2012). Depth determination of small shallow earthquakes in eastern Canada from maximum power Rg/Sg spectral ratio. *J. Seismol.*, 16(2), 107-129.