# Review of Kimberlite Exploration and Diamond Mine Developments along the Superior Craton: Implications for Eastern North Dakota

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**Introduction**

Beneath eastern North Dakota lays the Superior Craton and the potential for continued diamond exploration as well as diamond mine development. The Superior Craton is a large piece of Earth's crust that has been tectonically stable for over 2.5 billion years. The long duration of tectonic stability has allowed the underlying mantle to cool enough to develop the necessary temperature and pressure conditions to form diamonds at depths of more than 50 miles below the surface. Diamonds are transported to the surface through kimberlitic eruptions, which are volcanic eruptions that originate tens of miles below the surface and typically erupt along zones of weakness in Earth's crust such as faults and fractures. The resulting eruption commonly forms a pipe-shaped geologic feature called a kimberlite. Kimberlites typically occur in groups referred to as either fields or clusters. Although some kimberlites contain high concentrations of diamonds, most either contain relatively low concentrations or are completely barren of diamonds.

North Dakota's first diamond exploration test well was drilled during 2010 in Pembina County, located in the northeastern corner of the state (Nesheim, 2013). Although this diamond test well failed to encounter a kimberlite, the growing number of kimberlites being discovered and diamond mine projects being developed across the Superior Craton suggests diamond exploration will continue into North Dakota's future (figs. 1 and 2). Understanding the distribution and approximate emplacement (eruption) ages of currently discovered kimberlites across the Superior Craton may provide insight into exploring for, and predicting, the distribution of possible kimberlites within eastern North Dakota.

**Superior Craton Kimberlites**

To date, over a hundred kimberlites have been discovered across the Superior Craton, more than half of which were discovered within the past 15 years. Most of these kimberlites occur as clusters within the Canadian provinces of Ontario and Quebec (figs. 1 and 2). Moorhead et al. (2000) noted that the average distance between kimberlite fields/clusters across the Canadian Shield is similar to the typical global average distance of 250 miles (400 km) between large kimberlite fields. Globally, only 14% of kimberlites are diamondiferous (contain diamonds), most in concentrations too low for commercial mining. The percentage of diamondiferous Superior kimberlites appears to be higher than the global average, including 1) the Attawapiskat cluster – 16 of 18 kimberlites (89%) are diamondiferous and so far one kimberlite pipe is being commercially mined (Victor mine kimberlite), 2) the Kyle Lake cluster – 8 of 9 kimberlites are diamondiferous (89%) and two may be commercially mineable, 3) the Renard kimberlites (part of the Otish Cluster) – 4 out of 9 are not only diamondiferous, but are also projected to be commercially mined (figs. 1 and 2). Between these three kimberlite clusters, at least 28 of 36 kimberlites are diamondiferous (78%), of which eight or so may be commercially mineable (22%). Although continued kimberlite exploration and testing may lower the percentage of diamondiferous and commercially mineable kimberlites, so far the Superior Craton kimberlites appear to be more diamondiferous than the global average.

Kimberlites within a given cluster typically were emplaced within a similar geologic timeframe of millions to tens of millions of years. However, the approximate average age of emplacement between different clusters of kimberlites varies by up to a billion years!

**Photograph by Tom Churchill of the Jerico Diamond Mine pit in Nunavut, Canada, retrieved through wikimedia.org on 11-20-15.*

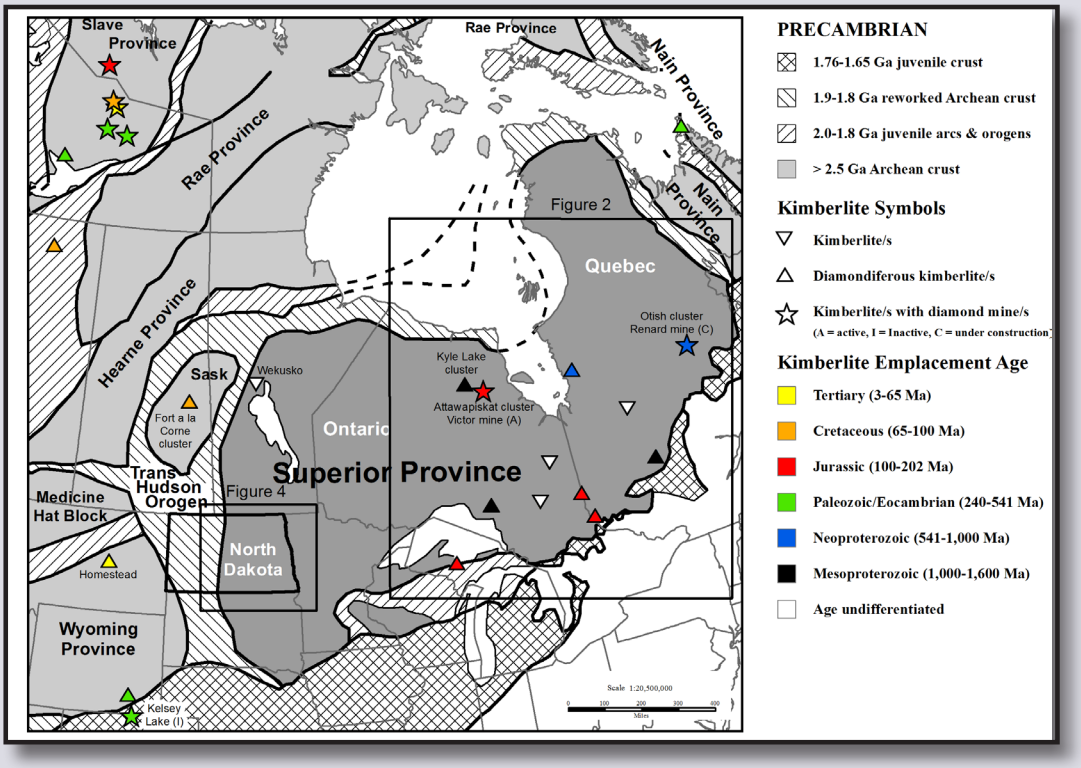


**Figure 1.** Regional map showing the extent of the Superior Craton with kimberlite and diamond mine distribution. Geology is modified from Whitmeyer and Karlstrom (2007) and the kimberlite-diamond mine information is compiled from Moorhead et al. (2000), Heaman et al. (2003), and Stevenson et al. (2004).

The Victor kimberlite was initially discovered in 1987 within northern Ontario, in an area where De Beers had been conducting kimberlite exploration since 1962 (fig. 1). Construction on the Victor mine, however, did not begin until nearly 20 years later, in February 2006. Commercial diamond production from the Victor mine began during mid-2008, and is expected to last at least until 2018 with a mine extension project planned to extend commercial production beyond that date. Average diamond production from the Victor mine has averaged 0.6 million carats per year.

The kimberlites across the Superior Craton can be divided into three age groups: Jurassic, Neoproterozoic, and Mesoproterozoic (Stevenson et al., 2004). Two of the youngest kimberlites clusters within the Superior Craton are the Attawapiskat and Kyle Lake clusters, which were emplaced during the Jurassic, approximately 130 million years ago (fig. 2). The Wawa and Desmaraisville clusters are currently the oldest sets of kimberlites, which were emplaced during the Mesoproterozoic, approximately 1.2 to 1.1 billion years ago (fig. 2). A third set of intermediate-aged kimberlites were emplaced during the Neoproterozoic, approximately 630 million years ago, and includes the Otish and Wemindij kimberlite clusters (fig. 2).

**Review of Current Superior Craton Diamond Mine Projects**

*Victor Diamond Mine – Ontario, Canada (owned and operated by De Beers)*

The Victor kimberlite is part of the Attawapiskat kimberlites, a group of 18 kimberlites that form a linear northwest trend along the northern margins of the Superior Craton. The Attawapiskat kimberlites were emplaced along the Winisk River Fault during the mid-Jurassic, 155 to 180 million years ago (Sage, 2000). The Attawapiskat kimberlites erupted through Ordovician- and Silurian-aged carbonate sediments and are overlain by 65-130 ft. (20-40 m) of Quaternary till and glaciomarine sediments (VMEP proposal, 2012). Within the current area of the Victor mine and proposed extension, Quaternary till and glaciomarine sediment thickness is 65 ft. (20 m) or less.

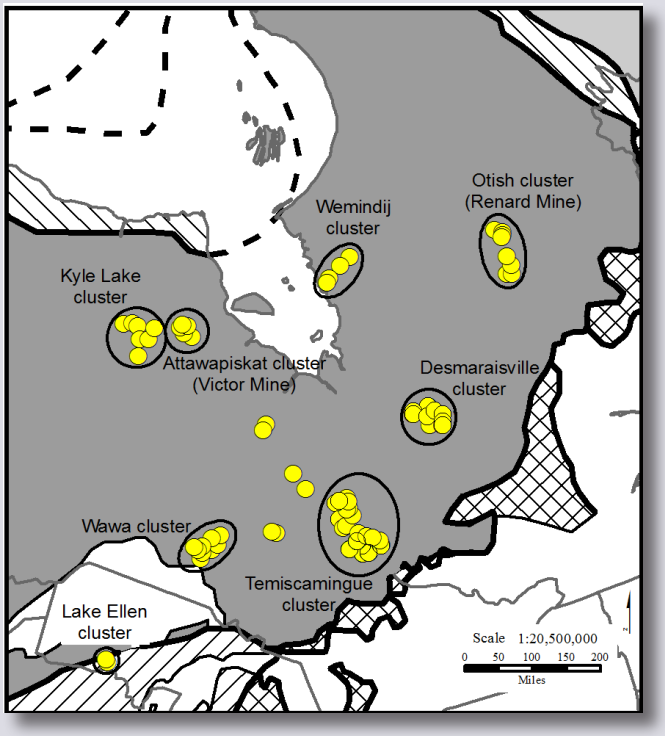


**Figure 2.** Kimberlite distribution map of eastern Ontario and southern Quebec. Kimberlite locations are depicted by yellow circles and are borrowed from Bagnell et al. (2013). The area of the figure 2 map is displayed on figure 1. As a spacial reference, both the Desmaraisville and the Temiscamingue cluster would fit into eastern North Dakota.

*Renard Diamond Mine – Quebec, Canada (100% owned and operation by Stornoway)*

The Renard kimberlites are located along the eastern portions of the Superior Craton within 2.7-billion-year-old granitic and gneissic rocks. The Renard kimberlites are part of the Otish cluster, a linear trend of kimberlite fields associated with the southern end of the Mistassini-Lemoyne structural zone. Emplacement of the Renard kimberlites occurred approximately 635 million years ago, making the Renard field one of the oldest kimberlite fields in Canada (Hunt et al., 2012). Glacial overburden within the Renard kimberlite area reaches thicknesses up to 100 ft. (30 m) and averages 40 ft. (12 m) in thickness (Bagnell et al., 2013).

Ten kimberlite pipes were identified in the Renard area of Quebec during 2001-2003 following five years of grassroots exploration. Four of the Renard pipes have been found so far to contain high concentrations of diamonds (Hunt et al., 2012), and may all eventually be commercially mined. Stornoway began construction on the Renard Diamond Project in July 2014 and commercial production is scheduled to begin by mid-2017. Stornoway estimates that the Renard Diamond mine will produce an average of 1.6 million carats per year, 2% of global supply, over an initial 11-year mine life (Stornoway Diamond Corporation, 2014).

**Implications for Eastern North Dakota**

As noted above, large kimberlite fields/clusters across the Canadian Shield and other areas of the world are typically spaced approximately 250 miles (~400 km) apart. There are, however, exceptions to this spacing where two separate kimberlites clusters are located less than 60 miles (~100 km) from one another (e.g. the Kyle Lake and Attawapiskat clusters figs. 1 and 2). The closest kimberlitic rock of the Superior Craton in proximity to North Dakota is the Wekusko kimberlite dike (Manitoba), which is located approximately 375 miles (~600 km) away (fig. 1). The Superior Craton extends beneath approximately 39,000 mi$^2$ (~100,000 km$^2$) of eastern North Dakota, which, depending on hypothetical kimberlite cluster location/s, could contain anywhere from zero to two kimberlite clusters spaced 250 miles (~400 km) apart (fig. 2). Given the distribution of known kimberlite clusters within eastern Ontario and southern Quebec, eastern North Dakota likely contains at least one substantial cluster of kimberlites (fig. 2).

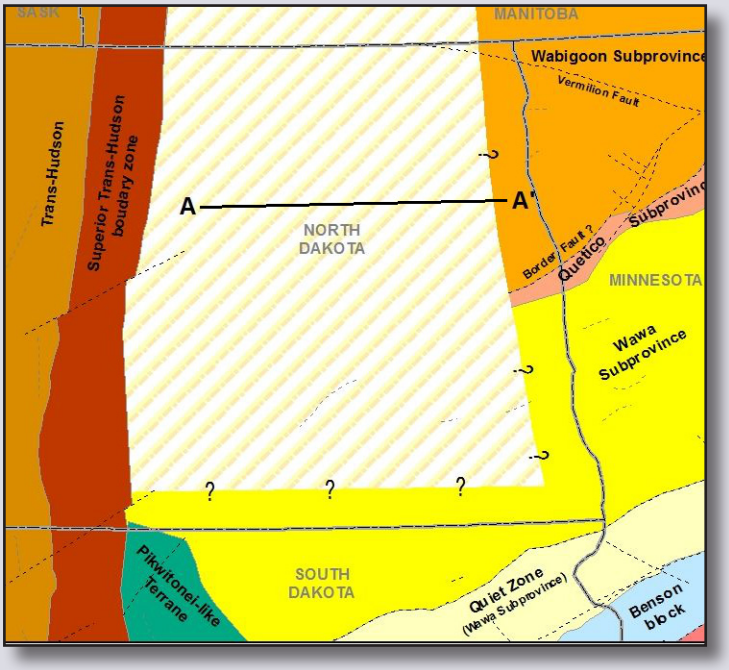


**Figure 4.** Basement terrane map of eastern North Dakota and the surrounding area with potentially significant structural features. The area of the figure 4 map is outlined on figure 1. Geology is modified from Southwick (1994) and McCormick (2010).

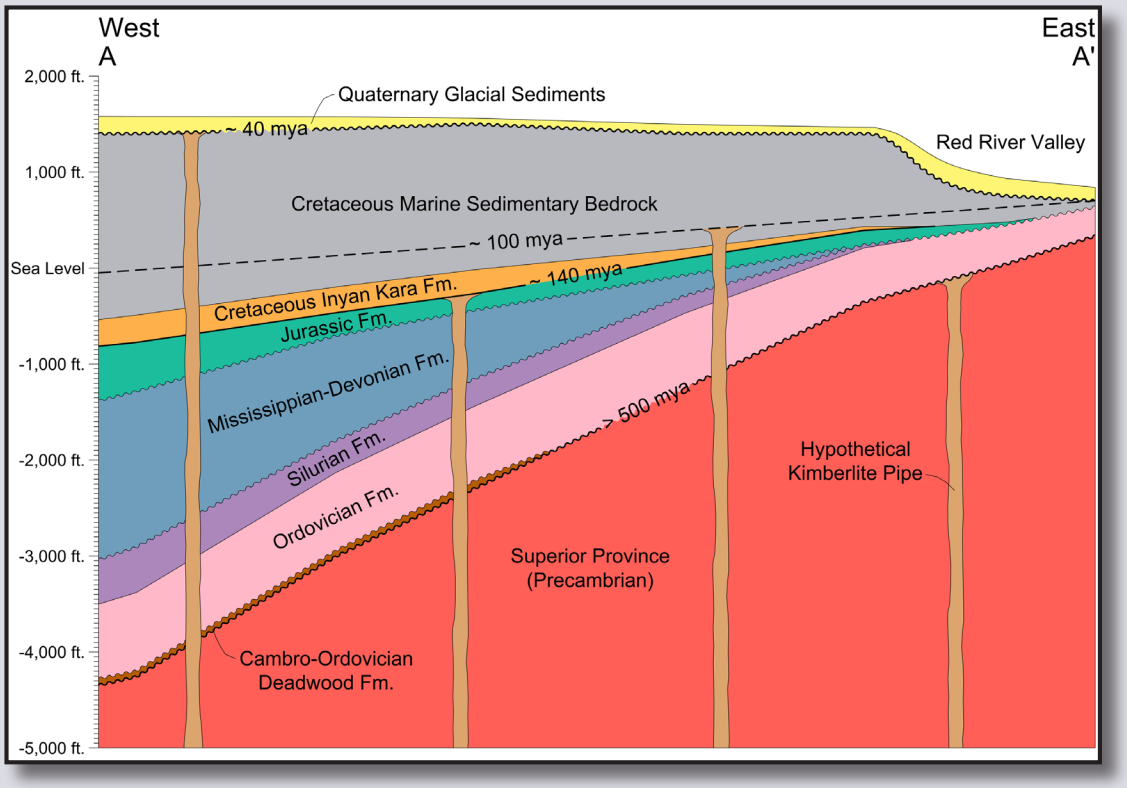


**Figure 3.** Schematic cross-section of eastern North Dakota depicting the potential approximate burial horizons of hypothetical kimberlites. The location of A-A' is shown in the figure 4 map. mya = millions of years ago.

The burial depths of hypothetical eastern North Dakota kimberlites are likely the greatest inhibitor to kimberlite exploration and discovery. Eastern North Dakota is positioned along the eastern flank of the Williston Basin, which has been an area of low topographic relief for much of the past 500 million years and has been infilled with tens to thousands of feet of sediment. Most of the Superior kimberlites that have been discovered to date are located in areas less proximal to sedimentary basins, were emplaced approximately 130 million to 1.2 billion years ago, and are typically buried by less than 100 ft. (30 m) of sediment (fig. 1). The youngest known cluster of kimberlites located near North Dakota are the Homestead kimberlites of eastern Montana, which were emplaced within the Wyoming Craton approximately 50 million years ago (Hearn, 2004) (fig. 1.). Given the emplacement ages of kimberlites in surrounding states and provinces, any prospective eastern North Dakota kimberlites were likely emplaced tens to hundreds of millions of years ago and are therefore likely buried by at least 50-500 ft. (15-150 m) of Quaternary glacial sediment (fig. 3). Kimberlites emplaced more than 100 million years ago would likely be buried by tens to thousands of feet of additional Cretaceous- to Cambrian-aged rocks (fig. 3). The older a hypothetical eastern North Dakota kimberlite, the more deeply buried it would be. Also, since North Dakota's sedimentary formations tend to all thicken and deepen westwards, towards the center of the Williston Basin, North Dakota kimberlites would become more deeply buried the further westward they are located.

Kimberlites across the Superior Craton are typically located along structural tectonic zones, which are approximately linear trends of brittle deformation (e.g. faults and fractures). The Vermilion fault zone passes through the northeastern corner of North Dakota, close to where the recent diamond test well was drilled in Pembina County, and a fault or fault zone marking the border between the Wabigoon and Quetico subprovinces may also extend into eastern North Dakota (fig. 4). These fault zones are prospective trends where kimberlites are more likely to have erupted through North Dakota's portion of the Superior Craton. Further delineation of fault/structural trends in eastern North Dakota would be beneficial to identifying areas to focus on for kimberlite and diamond exploration.

**Future Outlook**

Thirty years ago there were minimal (if any) known kimberlite occurrences within the Superior Craton and diamond exploration for the area was in its infancy. Ten years ago, in spite of a number of kimberlite discoveries across the Superior Craton, there was still not a single diamond mine either under construction or in production. Yet by the end of 2017, or whenever the Renard Diamond mine begins commercial production, diamond production from the Superior Craton will account for approximately 2% of the global annual diamond production. North Dakota is located nearly 200 miles (~320 km) from the closest known kimberlite occurrence within the Superior Craton and over 600 miles (~960 km) from the nearest diamond mine. However, diamond production across the Superior Craton will likely continue to grow in volume and spatial extent as kimberlite exploration continues, and diamond exploration along the Superior Craton may one day add diamonds to the list of North Dakota's mineral resources.

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