A5: KIMBERLITES IN THE CAYUGA LAKE REGION OF CENTRAL NEW YORK: THE SIX MILE CREEK, WILLIAMS BROOK, AND TAUGHANNOCK CREEK DIKES

DAVID G. BAILEY
Geosciences Department, Hamilton College, Clinton, NY 13323

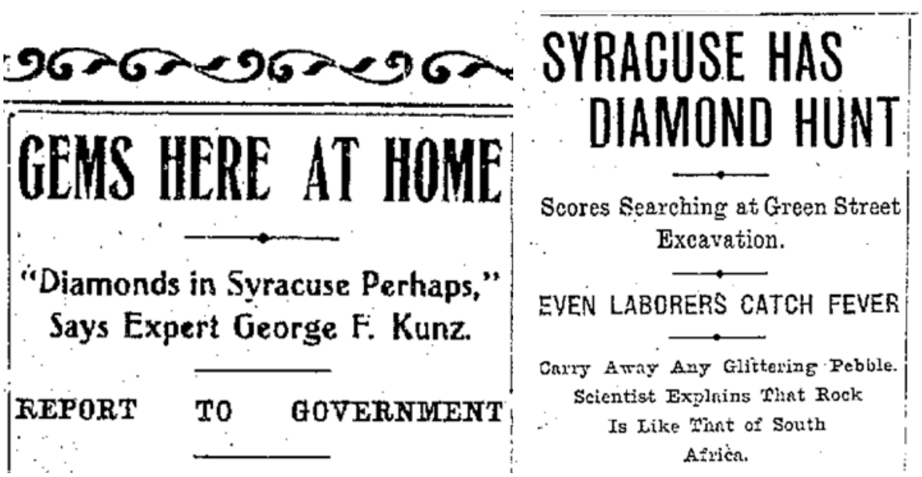
MARIAN V. LUPULESCU
New York State Museum, Research and Collections, 3140 CEC, Albany, NY 12230

JEFFREY R. CHIARENZELLI
Dept. of Geology, St. Lawrence University, Canton, NY 13617

INTRODUCTION

Diamonds in New York State? While it may be hard to believe, just over 100 years ago local residents and scientists thought that there was a very strong possibility of finding diamonds in upstate New York (Figure 1)[1]. This diamond rush lasted for the first few decades of the 20th century, but after numerous failed attempts, the diamond hunt was over and this interesting episode in New York State's history was largely forgotten.

Below we provide a chronological outline of the scientific discoveries and reports on the kimberlitic rocks of central New York, followed by detailed descriptions of the three dikes that will be visited on today's field trip. For a more detailed discussion of the ages and origins of these unusual rocks, the reader is referred to Kay et al. (1983) and Bailey & Lupulescu (2015).



GEMS HERE AT HOME

"Diamonds in Syracuse Perhaps," Says Expert George F. Kunz.

REPORT TO GOVERNMENT

SYRACUSE HAS DIAMOND HUNT

Scores Searching at Green Street Excavation.

EVEN LABORERS CATCH FEVER

Carry Away Any Glittering Pebble. Scientist Explains That Rock Is Like That of South Africa.

Figure 1: Early 20th century newspaper articles illustrating the period of diamond exploration in central New York. Left: Syracuse Herald, July 16, 1906, p.9; Right: Syracuse Post-Standard, Nov. 28, 1905, p.14

[1] NOTE: Most of the figures in this field trip guide are available on-line, and in color, at: *http://www.nysga-online.net/nysga-2017-guidebook-maps-and-images/A5*

HISTORY OF RESEARCH ON NEW YORK STATE KIMBERLITES

What prompted the diamond rush in central NY at the turn of the 20th century? It all started in 1887 with the recognition by British geologist Henry Lewis that the diamonds in South Africa were derived from unusual mica-bearing peridotites that he named "kimberlites" (1888; Mitchell, 1986). Interestingly, the mica peridotites of upstate New York were discovered and described over fifty years prior to this, making them the first kimberlitic rocks ever described in the scientific literature (Vanuxem, 1837, 1839). In his final report for the third geological district, Vanuxem (1842) described four narrow dikes of "serpentine and limestone…trap rock" (p.169) in a ravine east of Ludlowville, a small town north of Ithaca, New York. He also noted the existence of a "dyke on East Canada creek" (p.59) in the town of Manheim, and an interesting serpentine and mica-bearing "metamorphic rock" on "Foot-street Road" in Syracuse (p.109). While these are the first published descriptions of kimberlitic rocks, local geologists clearly knew about them for some time. According to Williams (1887a) and Hopkins (1914), Oren Root, then principal of Syracuse Academy, discovered the Green Street (formerly Foot Street) dike in 1837 and reported its occurrence to Vanuxem.

After the initial reports by Vanuxem (1837, 1839, 1842) and Beck (1842), only one significant scientific study of the New York kimberlites was published over the next twenty years. In (1858), T. S. Hunt published the first extended description, and partial chemical analysis, of the "Ophiolite of Syracuse, New York". While this study documented the ultramafic character of the rocks, their igneous origin was still not recognized; they were interpreted as "magnesian sediments which have been metamorphosed *in situ*" (p.239). In 1860, the rocks were briefly described by Geddes in a report to the New York State Agricultural Society (Geddes, 1860), and in 1874 Cornell University Professor O. Derby reported the existence of three dikes in Cascadilla Gorge and another one in Six-Mile Creek in a short paper in the Cornell Review. The Six Mile Creek dike was later described in a bit more detail by Simonds (1877). The New York "peridotites" were also mentioned in the third edition of Dana's "Manual of Mineralogy" (Dana, 1878).

Following Lewis's 1887 report at a meeting of the British Association for the Advancement of Science on the association of diamonds with "mica peridotites", there was an explosion in the number of published papers on all types of peridotitic rocks, including those in New York. Between 1887 and 1909 there were over 25 separate publications on the "serpentine dikes" or "peridotites" of central New York. The first to publish extensively on these rocks, and to recognize their intrusive origins was George H. Williams of Johns Hopkins University (Williams, 1887a, b, 1890a, b).

In 1891, Professor J.F. Kemp of Columbia College revisited Vanuxem's Ludlowville location but was able to identify only two of the four previously reported dikes. He also relocated and described the Six Mile Creek dike and the Cascadilla Creek dike in Ithaca. This paper contained a whole-rock chemical analysis of the Cascadilla Creek dike, the second published analysis of a New York peridotite.

In 1892, Professor C.H. Smyth of Hamilton College relocated Vanuxem's dikes on East Canada Creek in the town of Manheim and described the most prominent dike as a 25cm wide dike intruding along a fault plane (striking N20E) that juxtaposed the "Utica slate" with a "calciferous sand-rock". This was the first report relating the dikes to local structures. Smyth also noted the association of the dike with a one-inch thick vein of calcite, galena and pyrite. Smyth provided a chemical analysis and detailed petrographic description of the rock, and was the first to note the widespread occurrence of perovskite in the groundmass of the New York kimberlites (Smyth, 1892). In 1893, Smyth also reported the presence of melilite in the groundmass of the East Canada Creek dike, and on this basis, re-classified the dike as an alnoite (Smyth, 1893). (NB: Recent studies have not been able to confirm the presence of melilite in any of the New York State intrusions).

In 1895, another “dike” was discovered near Syracuse. The excavations for a new water reservoir three miles east of Syracuse in the town of Dewitt exposed large blocks of weathered peridotite (Darton and Kemp, 1895a, b). In-situ outcrop was not exposed, and the source of all available hand specimens was only the excavated material found on the banks of the reservoir. According to Darton and Kemp (1895b), the peridotite occurred as boulders buried in a greenish – yellow earthy matrix, and the size of the intrusion was estimated to be ~ 60 by 75 meters, based on the area covered by the earthy material. The intrusion was also noted to contain “many inclusions of various rocks” (p.457). A complete chemical analysis of the Dewitt intrusion was done at the United States Geological Survey and published in a number of subsequent USGS reports (Clarke, 1904; Clarke and Hillebrand, 1897; Darton and Kemp, 1895b).

At about the same time, two additional dikes were discovered in Manheim near the first dike originally reported by Vanuxem (Smyth, 1896, 1898). The largest dike, nearly 2 meters in width, was noted to be highly sheared and slickensided, and to contain long narrow “horses” of the country rock (Smyth, 1896). Smyth’s papers focused primarily on the presence or absence of melilite in the three dikes, and the mineralogical and chemical effects of weathering on the dikes.

With the expansion of the sewer system in the city of Syracuse at the close of the 19th century, additional exposures of the Green Street dike were uncovered, and described in some detail by Luther (1897), Clarke (1899) and Schneider (1902). The intrusion was described as varying in size and form along strike, from a single dike ~ 4 meters in width to a composite intrusion of multiple dikes and thin sheets with a total width of over 12 meters (Schneider, 1902). Commercial speculation heightened public and scientific interest in these rocks, resulting in multiple newspaper articles ("Gems here at home," 1906; "Serpentine rock of Onondaga rich in sparklers," 1902; "Syracuse has diamond hunt," 1905; "Would advance cash to probe stratums," 1902) and scientific publications (Kraus, 1904; Pattee, 1903; Schneider, 1902, 1903a, b; Smyth, 1902).

New dikes continued to be discovered and described in the Ithaca region (Barnett, 1905; Matson, 1905) and, at this time, Barnett concluded that a total of 25 dikes were known in New York State. This number kept increasing, as shortly after this four dikes were discovered in Clintonville (Smith, 1909), geographically in between Syracuse and Ithaca, and E. M. Kindle (in Williams et al., 1909) described five new dikes in the Ithaca area: two dikes in Indian Creek, two in Six-Mile Creek, and one east of the Central Avenue bridge.

After numerous failed attempts to find diamonds in any of the intrusions, scientific interest waned until Cornell Professor Pearl Sheldon and her students began studying the dikes in the Ithaca area (Martens, 1923a, b, 1924; Sheldon, 1921). These reports described over a dozen new dikes in the region, and Sheldon’s final publication emphasized the association of dike intrusion with faulting (Sheldon, 1927).

The next major study was conducted by Edwin Filmer (1939) who had the opportunity to conduct field work after a big storm in 1935 that washed sediment out of the ravines surrounding Ithaca, and exposed many new dikes. He also was the first to describe the large diatreme in the Poyer Orchard creek, and the small diamond washing operation that was set up here in the late 1930’s.

Over the next twenty years scientific focus moved to the Syracuse kimberlites, with Syracuse University Professor James Maynard and his students publishing the first detailed descriptions of most of the intrusions in the area (Apfel et al., 1951; Hogeboom, 1958; Maynard and Ploger, 1946; Van Tyne, 1958).

As scientific technologies advanced in the late 20th century, numerous researchers attempted to date the New York kimberlites. Zartman et al. (1967) published the first K/Ar and Rb/Sr ages on phlogopite grains extracted from two dikes, one near Ithaca and the other in the town of Manheim. The K/Ar ages ranged from 145 to 493 Ma, and the Rb/Sr ages ranged from 118 to 146 Ma. Zartman et al. recognized that the early Paleozoic ages were clearly incompatable with the known stratigraphic relationships, and attributed the old K/Ar ages to excess radiogenic argon and/or the retention of argon by old xenocrystic phlogopite. He concluded that the New York intrusions were of Late Jurassic to Early Cretaceous age. Subsequent K/Ar studies by Watson (1979) and Basu et al. (1984) confirmed the Late Jurassic to Early Cretaceous age of the New York Kimberlites with most ages between 120 and 150 Ma. The most recent radiometric dating on these rocks was done by Heaman and Kjarsgaard (2000) who extracted groundmass perovskite from two dikes northwest of Ithaca. The high precision U-Pb ages obtained on these samples ranged from 144.8 ± 3.2 to 147.5 ± 3.0 (Heaman and Kjarsgaard, 2000).

Two paleomagnetic studies were also done on dikes in the Ithaca region. The first, by Dejournett and Schmidt (1975), and the most recent and more extensive study by Van Fossen and Kent (1993). Both revealed a complex history of emplacement times and temperatures, with normal and reversed pole positions, and a previously unrecognized late Jurassic – early Cretaceous virtual geomagnetic pole position at 58^{o}N, 203^{o}E.

Foster (1970) provided an excellent and comprehensive review of the locations, mineralogy and petrology of kimberlites in the Ithaca region. Most of the subsequent work on these rocks was done by Cornell Professor S. M. Kay and her students on the macrocryst and xenolith mineralogy of the Ithaca area intrusions (Kay, 1990; Kay and Foster, 1986; Kay et al., 1983; Snedden, 1983; Snedden and Kay, 1981a, b).

Over the past twenty years, the authors, with the help of numerous colleagues and students, have compiled consistent and comprehensive data on the mineralogical and chemical compositions of all the kimberlitic intrusions in New York State. This has allowed us to identify large scale patterns and variations in Mesozoic magmatic activity across the region (Bailey and Lupulescu, 2007a; Bailey and Lupulescu, 2007b, 2009, 2015; Lupulescu et al., 2007; Lupulescu et al., 2002; MacDougall and Bailey, 2009; Rauscher et al., 2003). A general overview and summary of our current understanding of these unusual rocks is presented in the following section.

GENERAL FEATURES OF NEW YORK STATE KIMBERLITES

Geographic & Geochemical Groups

Over the past 180 years, a total of approximately 90 distinct kimberlitic intrusions have been identified in central New York State. The vast majority occur in two distinct clusters: one in the Ithaca / Cayuga Lake region, and the second in and around the city of Syracuse. A few additional dikes have been observed as far north as Ogdensburg, and as far east as "Big Nose" on the Mohawk River in Montgomery County. Most of the intrusions are thin (<30 cm wide) tabular dikes, with vertical dips and N-S strikes (± 10^o) (Bailey and Lupulescu, 2007b; Foster, 1970) . The widest dike is the one exposed in Williams Brook (~3.5 m) which will be our second stop on this trip. In addition to the numerous dikes, there are two fairly large and irregular intrusions that appear to be small diatremes: one in the Ithaca region (Poyer Orchard diatreme with a maximum dimension ~ 50 m)(Foster, 1970), and one in the Syracuse region (the Dewitt Reservoir diatreme with a maximum dimension of ~75 m)(Darton and Kemp, 1895b).

Each of the intrusions is, in some way, mineralogically and/or chemically distinct. Nevertheless, four broad groups of intrusions (designated Groups A, B, C & D) have been recognized, each with shared chemical and mineralogical features (Table 1; Figures 2 and 3) (Bailey and Lupulescu, 2015).

Kimberlites belonging to Groups A and B are only found in the Ithaca region. Group A dikes are only exposed along the western margin of Cayuga Lake and, in fact, very likely represent a single intrusion that crops out intermittently in en echelon segments along strike. These dikes tend to be quite wide (1-4 m), serpentine-rich, very dark green to black in color, and relatively resistant to weathering. They also are TiO_2-rich and contain abundant perovskite. Our second stop today will be to examine one the most easily accessed Group A dikes – the Williams Brook dike.

Group B dikes are the most abundant, and the most compositionally diverse. These dikes tend to be very narrow, typically < 10 cm, although dikes up to 1.5 m do occur. They also tend to be very carbonate-rich, pale tan-green in color, and highly weathered. Two of our stops today (at Six Mile Creek and Taughannock Creek) will be to examine Group B dikes.

Group C kimberlites are only found in the Syracuse Region, and appear to represent a distinct style and episode of igneous activity in central New York. The only intrusion that is still readily accessible are fragments of the Dewitt diatreme exposed along the flanks of the small water Reservoir on the LeMoyne College campus (Bailey and Lupulescu, 2012). These intrusions tend to be very dark colored, contain abundant olivine macrocrysts (usually serpentinized), and common garnet and clinopyroxene macrocrysts.

Group D kimberlites are represented by two, ~ 25 cm wide dikes exposed along the banks of East Canada Creek on the Herkimer – Montgomery County line. (NB: A third, ~ 2 m wide dike described by Smyth (1896) could not be relocated). These dikes are characterized by being extremely carbonate-rich and serpentine-poor, with large (up to 2 cm long) phlogopite macrocrysts. They are extremely TiO_2-rich, and as a result, contain abundant perovskite and secondary titanate minerals in the matrix.

Table 1. Whole-rock chemistry of Taughannock Creek (TC), Williams Brook (WB), and Six Mile Creek (SMC) kimberlite dikes (from Bailey & Lupulescu, 2015).

Dike	**TC**	**TC**	**TC**	**TC**	**TC**	**TC**	**TC**	**WB**	**WB**	**WB**	**SMC**	**SMC**
Sample	T1	T1b	T2	T5c	T6	T7a	TC-3	W1	W2	W2r	SMC-1	SMC-2A
	Major Element Oxides (XRF wt.%)											
SiO_2	27.34	24.53	19.77	29.32	17.27	15.42	28.45	35.63	32.05	32.65	7.90	23.59
TiO_2	1.53	1.85	1.50	1.63	1.60	1.33	1.61	2.73	2.42	2.41	1.58	1.25
Al_2O_3	2.89	3.50	2.80	3.41	3.38	3.16	3.94	4.16	3.09	3.17	3.01	2.86
FeO*	8.42	6.95	6.33	8.18	5.40	4.83	6.89	10.51	9.14	9.28	3.61	6.91
MnO	0.21	0.22	0.37	0.22	0.53	0.73	0.35	0.20	0.17	0.17	0.64	0.22
MgO	17.81	14.71	16.94	19.24	13.32	11.43	13.03	27.54	26.38	26.48	6.49	15.72
CaO	15.29	21.12	20.09	13.81	25.38	28.51	19.83	6.55	9.81	10.00	37.37	20.28
Na_2O	0.16	0.21	0.17	0.21	0.21	0.19	0.14	0.06	0.11	0.09	0.09	0.21
K_2O	1.37	1.49	1.31	1.70	1.57	1.28	1.37	2.40	1.94	2.00	0.89	1.63
P_2O_5	1.13	1.41	1.06	1.20	1.08	0.99	1.14	0.65	0.41	0.40	0.62	0.91
Maj.	76.50	75.98	70.67	79.49	70.04	67.86	76.74	90.44	85.51	86.65	62.21	73.57
Tr. Ox.	0.87	1.19	0.86	1.84	0.95	0.85	2.95	0.93	0.75	0.68	0.78	0.77
LOI	21.28	20.78	27.39	17.19	27.79	30.17	19.43	9.43	12.73	12.85	35.15	24.39
TOTAL	98.65	97.95	98.92	98.52	98.79	98.88	99.12	100.80	98.99	100.18	98.14	98.73
	Trace Elements (XRF ppm)											
Ni	988	913	940	945	978	672	904	1004	1013	998	790	801
Cr	1388	1627	1437	1448	1518	1215	1625	1788	1875	1769	1078	1247
Sc	24	26	20	22	23	19	19	24	17	16	15	17
V	262	313	235	313	322	293	301	320	227	215	225	238
Ba	1436	2564	1152	3333	1529	1505	20949	2198	840	860	3656	2646
Rb	50	55	51	63	58	48	58	129	80	83	41	69
Sr	1473	2153	1815	7821	1772	1783	4577	528	511	509	1062	1561
Zr	287	343	273	282	282	238	238	298	142	139	175	210
Y	22	26	25	24	27	30	22	14	11	10	28	17
Nb	183	216	172	181	173	141	178	137	110	114	146	189
Ga	9	10	8	10	8	7	9	13	8	10	6	7
Cu	68	91	63	81	72	66	74	87	63	65	57	55
Zn	74	77	61	78	83	32	85	79	66	73	59	81
Pb	10	13	17	13	15	22	10	6	8	4	17	13
La	160	222	141	144	187	117	129	84	81	84	123	164
Ce	292	428	265	280	341	222	235	151	152	153	226	266
Th	21	29	21	15	21	21	19	14	13	12	18	24
Nd	112	161	97	105	125	87	84	58	59	55	83	92
	Trace Elements (ICP-MS ppm)											
La	162.28	229.96	145.74	157.98	184.45	119.75	142.01	84.41	84.53	80.95	125.05	163.59
Ce	298.48	443.34	269.89	286.77	348.05	228.35	237.69	152.69	156.04	148.37	226.46	274.52
Pr	32.66	48.67	29.50	31.15	38.04	25.22	24.22	16.58	16.85	16.14	24.51	28.32
Nd	114.85	171.07	104.76	110.74	135.18	89.40	82.80	57.11	58.62	56.16	84.89	94.95
Sm	17.12	23.86	16.32	17.12	19.76	15.17	12.65	8.56	8.45	8.25	15.11	13.70
Eu	4.28	5.35	4.35	4.78	4.99	4.16	3.31	2.37	2.31	2.24	4.07	3.63
Gd	11.22	14.02	11.57	11.57	12.85	12.14	9.00	5.88	5.49	5.42	12.97	8.48
Tb	1.30	1.54	1.36	1.38	1.44	1.44	1.15	0.71	0.62	0.61	1.47	1.05
Dy	5.85	6.81	6.30	6.38	6.46	6.71	5.55	3.45	2.82	2.75	6.44	4.85
Ho	0.89	1.05	0.99	0.97	1.02	1.12	0.94	0.55	0.42	0.41	1.04	0.73
Er	1.86	2.17	2.09	2.04	2.14	2.55	2.12	1.24	0.85	0.83	2.32	1.55
Tm	0.22	0.26	0.24	0.24	0.26	0.31	0.27	0.14	0.10	0.10	0.29	0.18
Yb	1.14	1.33	1.24	1.24	1.28	1.79	1.49	0.77	0.52	0.50	1.57	0.98
Lu	0.16	0.19	0.17	0.17	0.18	0.26	0.21	0.11	0.07	0.07	0.23	0.13
Ba	1458	2566	1141	3367	1517	1488	20504	2231	853	834	3724	2663
Th	20.7	24.3	19.3	19.5	18.5	15.0	15.9	11.9	12.3	11.0	18.1	23.8
Nb	189.6	227.3	176.8	189.5	177.3	145.2	185.5	141.5	115.0	110.5	149.5	191.3
Y	22.0	25.6	25.4	24.0	26.6	30.0	24.7	14.1	10.1	9.8	28.2	17.9
Hf	6.3	7.7	6.0	6.5	6.2	5.2	4.9	7.3	3.5	3.4	4.2	4.7
Ta	9.6	11.7	9.4	9.6	9.1	7.5	8.1	7.7	7.9	8.4	6.4	7.0
U	4.5	5.3	4.1	4.5	4.5	3.9	4.4	3.3	2.2	2.1	4.1	5.7
Pb	10.8	14.5	13.7	12.3	11.1	11.4	13.7	7.0	5.7	4.4	16.9	13.6
Rb	49.0	54.9	49.0	63.7	56.1	45.4	52.5	125.0	76.8	76.1	40.3	66.3
Cs	2.6	1.9	2.1	1.9	1.4	1.1	3.5	2.7	2.7	2.5	1.0	4.6
Sr	1496	2186	1819	7583	1775	1793	4227	557	509	487	1075	1553
Sc	21.9	26.7	20.8	22.5	22.5	18.2	18.0	23.4	16.6	16.3	15.5	17.2
Zr	279	335	263	282	268	224	237	281	132	135	178	209

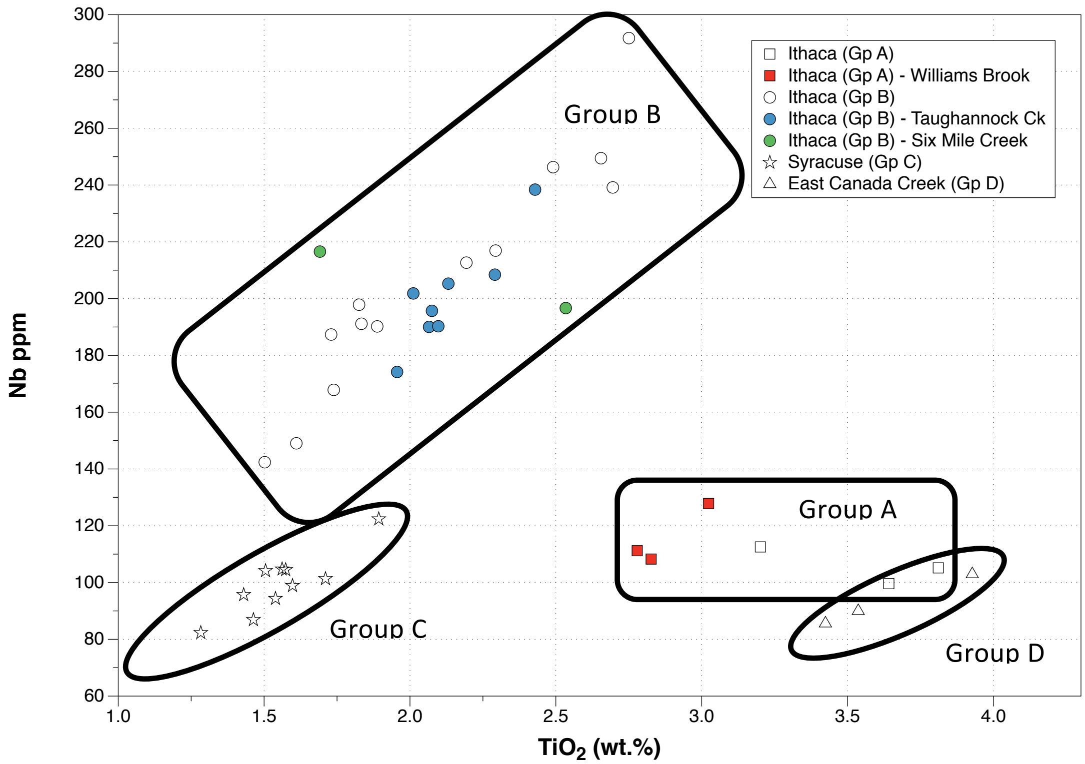


Figure 2. Nb versus TiO_2 scatter plot of New York State kimberlite whole-rock compositions showing the four major groups of intrusions.

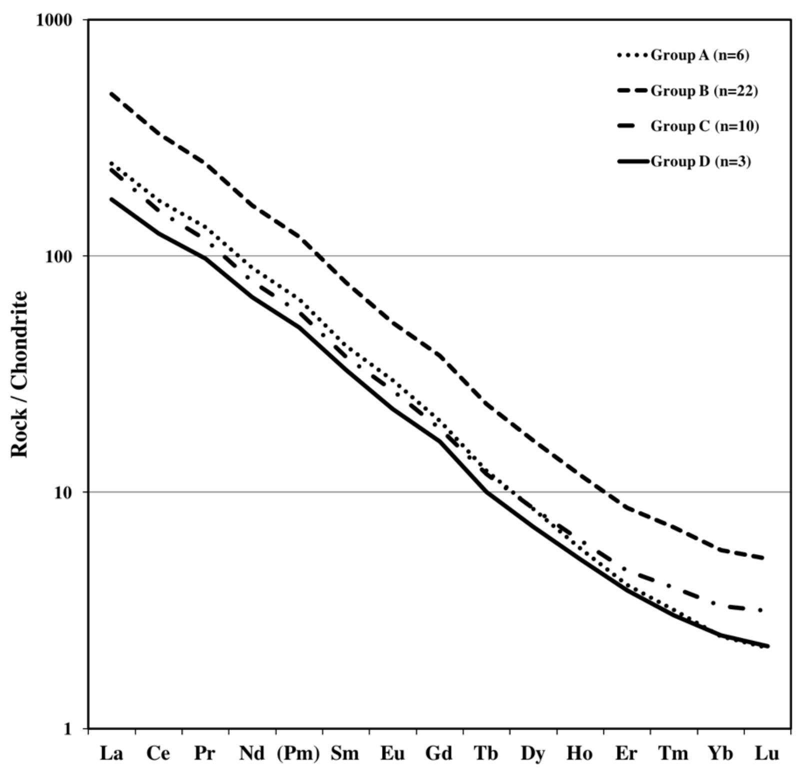


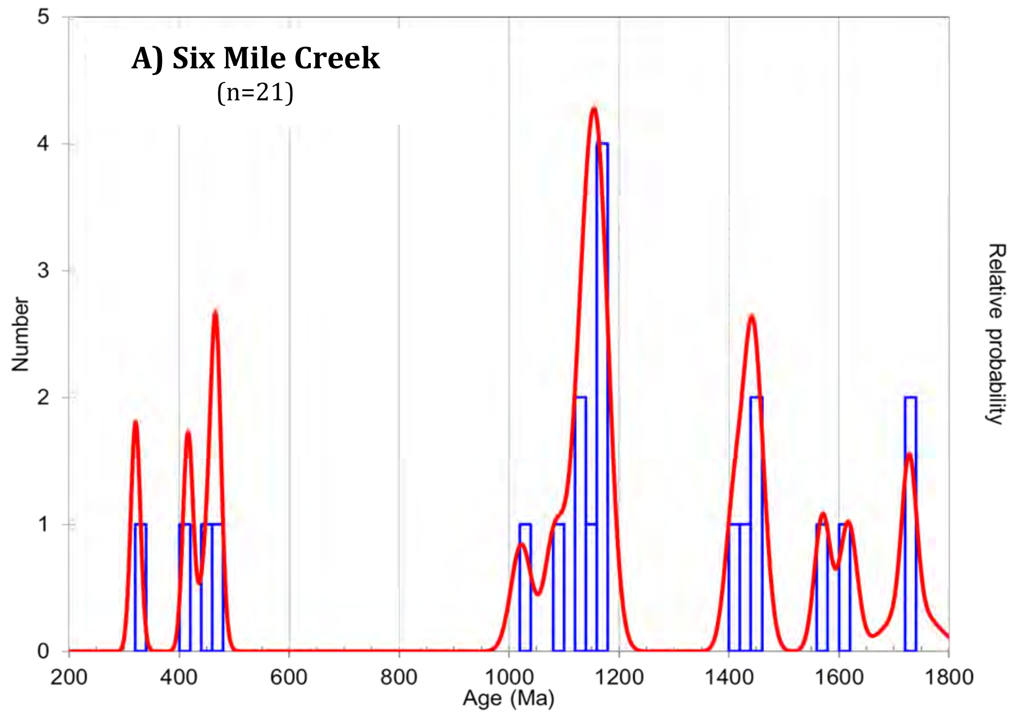
Figure 3. Average chondrite-normalized REE profile of the four groups of kimberlite intrusions in New York State (Bailey and Lupulescu, 2015).

Age and Origin

Despite many attempts, accurate emplacement ages for the kimberlites of New York have been difficult to obtain; published ages range from 500 to 110 Ma (Basu et al., 1984; Watson, 1979; Zartman, 1988; Zartman et al., 1967). Since nearly all of the kimberlites intrude Upper Devonian sedimentary units, reported ages > 400 Ma are clearly inaccurate. These ages, many of which are K-Ar ages on phlogopite macrocrysts of xenocrystic origin, do not record intrusion ages. The most accurate emplacement ages are high precision U-Pb dates of 144.8 ± 3.2, 146.7 ± 2.4, and 147.5 ± 3.0 obtained on groundmass perovskite grains from two dikes on the western margin of Cayuga Lake (Heaman and Kjarsgaard, 2000). Unfortunately, all three samples were collected from two dikes, both belonging to compositional Group A, and very likely, are part of a single intrusion. As a result, emplacement ages for most of the kimberlitic intrusions in New York State are still not well constrained. Compilation of published ages suggests that there may have been two distinct magmatic episodes: the earliest ~146 Ma (Group A and Group D intrusions), followed by emplacement of the largest number of intrusions ~125 Ma (Group B and Group C intrusions) (Bailey and Lupulescu, 2015).

We recently found and extracted a number of zircon grains from two of the intrusions we will be visiting today: The Six Mile Creek and Taughannock Creek dikes. The zircons almost certainly are derived from disaggregated xenoliths; none have been observed as discrete matrix grains in thin section. Approximately one kilogram of rock was collected from each dike, and zircons ranging in size from 25-150 microns were separated by standard techniques at the Arizona LaserChron Center at the University of Arizona. The separated zircons were imaged by scanning electron microscope including both back scattered electron (BSE) and cathodoluminscence (CL) modes, and multiple spots were selected for analyses. Interestingly, the two dikes contain very different zircon populations (Figure 4), indicating that each encountered and sampled very different lithologies on their way to the surface. Not surprisingly, most of the zircon grains found in the Six Mile Creek dike are either Mesoproterozoic (1050 to 1200 Ma) or Early Paleozoic (400-500 Ma) in age, most likely derived from the presumed Grenville age lower crust and the overlying Paleozoic platform rocks. The Proterozoic zircons are very likely inherited detrital grains also derived from the Paleozoic sedimentary sequence.

The Taughannock Creek dike, in contrast, contains a much larger population of zircons, but with a narrower range of ages, with nearly all being Neoproterozoic (550 to 1000 Ma). These are uncommon ages for basement rocks exposed to the north in the Adirondack Mountains, suggesting the possibility of previously unrecognized crustal terrane being present beneath western New York State, or having supplied detrital zircons to the overlying Paleozoic sedimentary sequence. We hope to follow up on this preliminary study with a more comprehensive survey of the zircon and perovskite populations present in New York State kimberlites, including the Hf isotopic compositions of the different zircon populations.



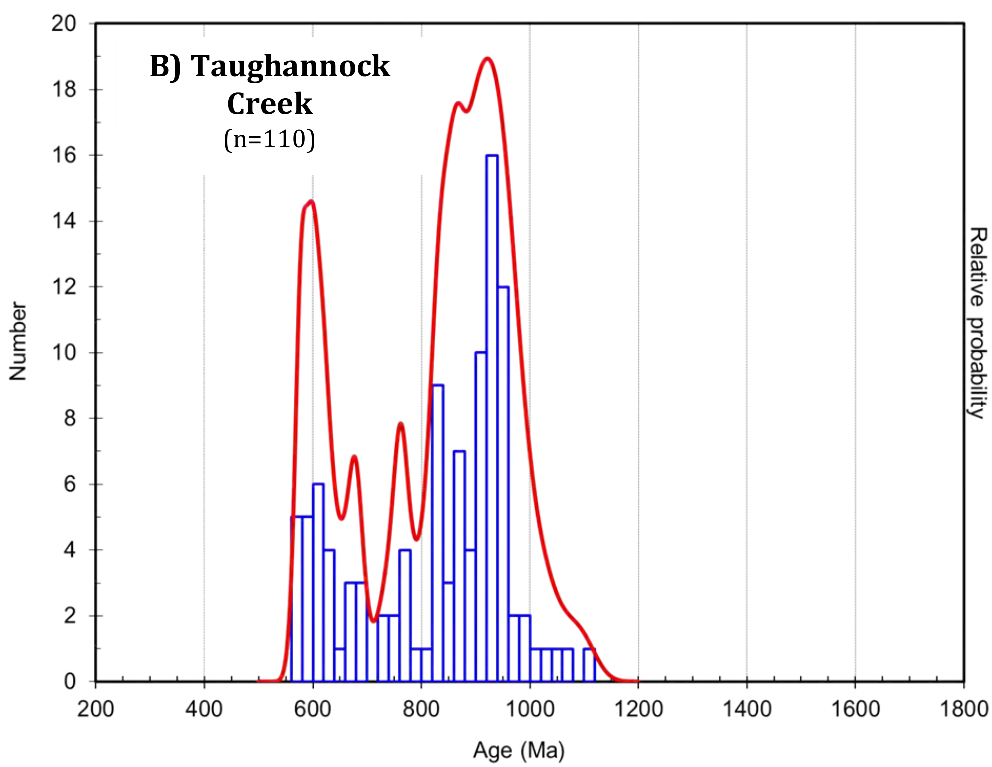


Figure 4. U-Pb ages obtained on zircons extracted from the A) Six Mile Creek, and B) Taughannock Creek kimberlite dikes. Individual analyses shown as stacked blue bars; relative age probabilities shown as red curve.

Currently, there are two theories that have been put forth to explain the origin of the kimberlitic rocks in New York State (Figure 5): 1) they are part of a chain of small, alkaline intrusions in eastern North America related to passage of the North American plate over the Great Meteor hot spot (Heaman and Kjarsgaard, 2000); or 2) they are part of a belt of kimberlitic intrusions along the western flanks of the Appalachian Mountains that were intruded along old structures that were reactivated by crustal extension related to rifting and opening of the Atlantic Basin (Parrish and Lavin, 1982). Bailey and Lupulescu (2015) concluded that the New York kimberlites have macrocryst assemblages and geochemical and isotopic characteristics consistent with derivation from a relatively shallow, asthenospheric, garnet lherzolite source. Consistent with the model of Parrish & Lavin (1982), they argued that far field stresses related to the opening of the Atlantic Ocean reactivated major crustal structures and provided pathways for small volume, volatile-rich magmas to ascend and intrude the Paleozoic sedimentary platform rocks of central New York.

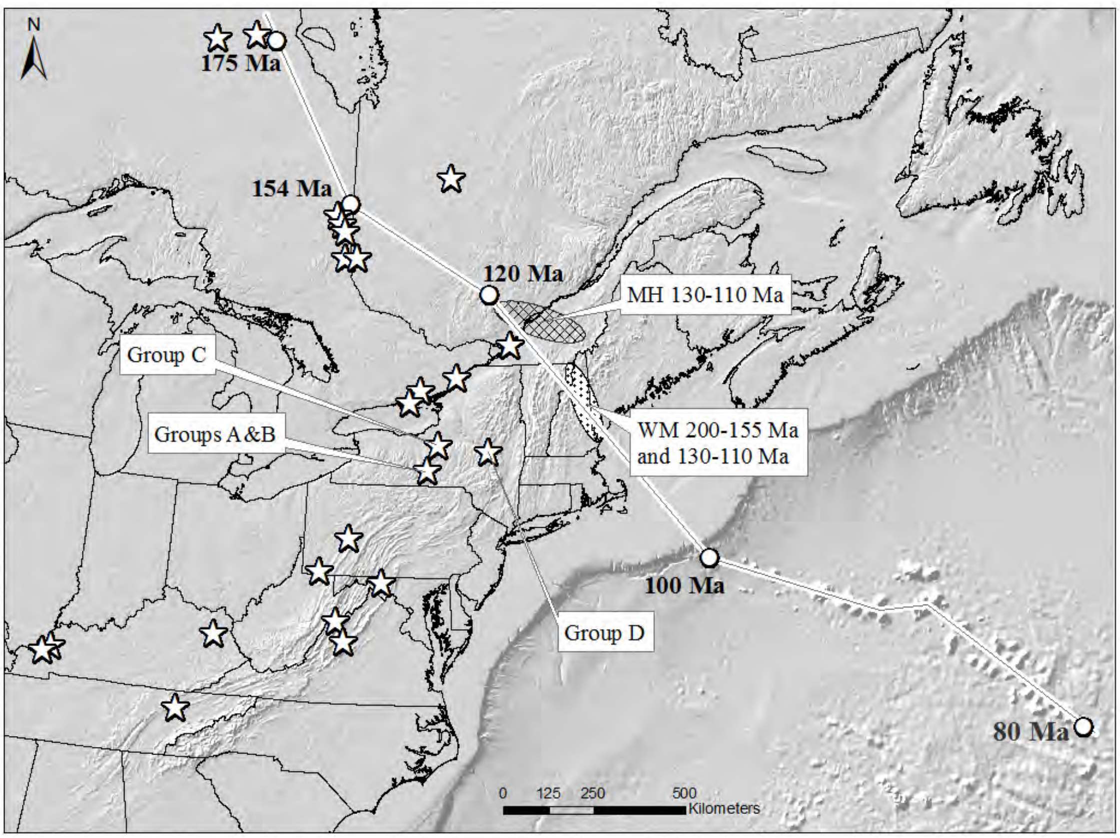


Figure 5. Map of eastern North America showing locations of kimberlitic intrusions (white stars), the path and ages of magmatism associated with the Great Meteor Hot Spot (white line and circles), and the locations of the four major groups of intrusions in central New York State (Groups A through D). MH = Monteregian Hills; WM = White Mountains.

FIELD GUIDE

Meeting Point: Wegman's Supermarket Parking Lot, southwest corner, 500 S Meadow St, Ithaca, NY

Meeting Point Coordinates: 42.43394, -76.51109

Meeting Time: 9 AM, Saturday, October 7, 2017

General Information:

All three stops will be in creeks surrounding Cayuga Lake where erosion has exposed these small intrusions. Public access is allowed in all three locations for fishing or hiking, but please respect the private property adjacent to all three sites.

Please do not collect samples of the Six Mile Creek or Taughannock Creek dikes!! The Six Mile Creek dike that we will visit is undoubtedly the best exposure of any of the New York State kimberlites. It is a beautiful exposure of a geologically and historically important rock; the outcrop should be preserved and not subjected to unnecessary sampling. The Williams Brook dike is much larger, and loose blocks can often be found in the streambed; sampling of this material for research or educational use is encouraged.

STOP #1: Six Mile Creek

Parking Location and Coordinates: Parking lot for Mulholland Wildflower Preserve, south off of Giles Street, on east side of Six Mile Creek. (42.43266, -76.48417)

Follow the nature trail on the east side of Six Mile Creek for ~600 m (~ 1/3 mile); two dikes will be exposed and clearly visible in the streambed. The largest is ~ 20 cm-wide, and stands out prominently from the surrounding shales. The second is a cluster of small, anastomosing dikelets ranging from 1 to 8 cm in width. These are two of the seven dikes that have been observed in a 4 km long stretch of the Six Mile Creek drainage southeast of Ithaca (Figure 6).

History of the Six Mile Creek (SMC) dikes

The earliest known mention of intrusive dikes along Six Mile Creek was by Cornell Professor of Geology Orville Derby in the student newspaper where he stated that the best dike for students of geology to study was one exposed in Six Mile Creek (Derby, 1874 in Kemp, 1891). Simonds (1877) noted that many of the dikes in Six Mile Creek "thin out before reaching the surface" (p.51), and Kemp (1891) was the first to prepare and describe thin sections of the dikes which he noted proved the dikes to be "eruptive rock in advanced decomposition"(p.411). Subsequent studies identified a total of seven distinct dikes, the largest being the 20 cm-wide dike we will visit on this trip (Figure 7) (Filmer, 1939; Martens, 1924; Matson, 1905; Williams et al., 1909). In addition to these dikes, one small diatreme was also identified and described as a 2.5 m by 3 m ellipsoidal mass that had been partly excavated and "washed" by earlier gem hunters (Filmer, 1939).

Other than a single petrographic report provided by Foster (1970), no modern analytical work had been done on any of the Six Mile Creek kimberlites prior to a study in 2015 by Hamilton College student Deanna Nappi. Nappi (2015) collected samples from three of the SMC dikes and presented detailed petrographic descriptions, mineral chemistry, and whole-rock analyses in her undergraduate thesis. Much of the information presented below is a summary of the results of her research.

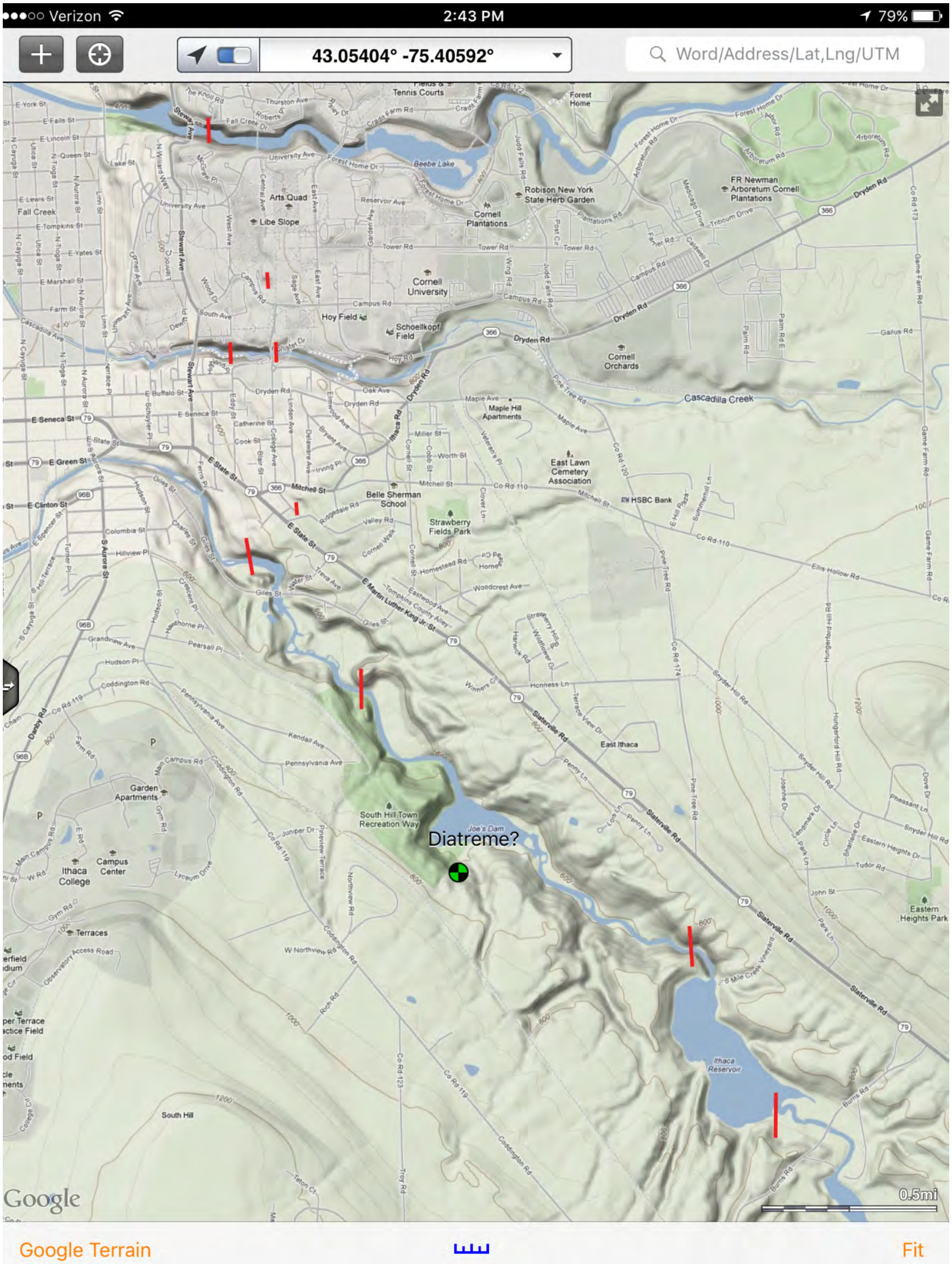


Figure 6. Shaded relief map of the Six Mile Creek drainage southeast of Ithaca, NY showing reported locations of kimberlite dikes (red lines), and one possible diatreme (green and black circle). Locations compiled (and approximated) from information in Williams et al. (1909), Martens (1924), Filmer (1939), and Foster (1970).

Figure 7. Kimberlite dike exposed at Stop #1 along Six Mile Creek. Dike is ~ 20 cm wide, and intrudes along the prominent N-S oriented fracture set in the surrounding shales.

Petrography of Six Mile Creek Kimberlites

Three Six Mile Creek dikes were sampled and 22 thin sections were made and examined using a polarized light microscope and a scanning electron microscope with an energy dispersive x-ray fluorescence spectrometer. Like all of the central New York kimberlites, the Six Mile Creek dikes are petrographically complex, with textures and phase assemblages varying from sample to sample. Overall, the SMC dikes are characterized by abundant macrocrysts of phlogopite and olivine (almost always serpentinized) in a carbonate-rich matrix, typical of the Group B kimberlites found throughout the Ithaca region (Table 2). Other observed macrocrysts include clinopyroxene (Figure 8), garnet, spinel, and orthopyroxene. While some of these macrocryst phases may actually be phenocrysts, most are clearly the remnants of disaggregated xenoliths, and most of the phases are not in equilibrium with the host magma, as evidenced by the rounded and embayed nature of most grains, and distinct reaction rims on others.

Olivine is the most abundant macrocryst in the SMC dikes, but virtually all of the grains have been replaced by a mixture of serpentine, calcite, and magnetite (Figure 8). All of the pseudomorphs are rounded and exhibit irregular morphologies; the largest grains have diameters ~ 4 mm. A few unaltered olivine grains were observed in the chilled portion of the small dike exposed at location 1; these grains have compositions ranging from $Fo_{90\ \mathrm{to}\ 92.5}$ (Nappi, 2015).

Phlogopite is the second most abundant macrocryst phase in the SMC dikes; most grains are tabular and often flow-aligned, and individual grains can reach 5 mm in length. Larger grains tend to be rounded, and many are partly altered to serpentine and/or calcite along cleavage planes. In thin section the grains range from nearly colorless to strongly pleochroic yellow-orange in PPL, and compositionally, all are Fe-bearing phlogopites with 5-8 wt.% FeO and 1-3 wt.% TiO_2.

While scarce, garnet grains are also found as individual macrocrysts and as grains in xenoliths (Figure 9). Similar to other Group B intrusions, the garnets in the SMC dikes belong to two major compositional groups, one a Cr-bearing pyrope, the other an almandine-rich garnet (Figure 10). While the Cr-bearing pyropes are clearly of mantle origin, no garnets from any of the New York State kimberlites are "G10" garnets with compositions indicative of having come from a high diamond potential mantle source (Bailey and Lupulescu, 2015; Grutter et al., 2004).

Clinopyroxene grains are also common as discrete macrocrysts and as part of larger xenoliths (Figures 8 and 9). Most of the macrocrysts are rounded and distinctly zoned with a colorless core surrounded by a pale yellow-green rim. All are diopsides; the rims are distinctly more FeO and TiO_2-rich than the cores (up to 6 and 1.5 wt. %, respectively). In the xenoliths, the clinopyroxenes are pale green and contain up to 1 wt. % Cr_2O_3 (Nappi, 2015).

Orthopyroxene is also common as both macrocrysts and as grains within xenoliths, both with compositions ~ En_{90}. Most of the orthopyroxene grains contain thin clinopyroxene exsolution lamellae. While orthopyroxene has been reported in other New York State kimberlites (Darton and Kemp, 1895b; Jackson, 1982), we have not positively identified distinct orthopyroxene macrocrysts in any intrusion other than the dikes at Six Mile Creek.

Spinels are also common as individual anhedral, embayed macrocrysts, and as inclusions in xenoliths. Typical of kimberlitic rocks in general, a wide range of spinel compositions can be found in a single intrusion (Figure 11) (Barnes and Roeder, 2001; Roeder and Schulze, 2008). In thin section, spinel macrocrysts in the Six Mile Creek dikes range in color from opaque, to brown, to red-brown, and even to green. While individual grains are chemically homogeneous, the diversity of spinel compositions indicates that most are xenocrysts derived from a variety of disaggregated xenoliths.

The matrix of the Six Mile Creek kimberlites is very fine-grained and composed predominantly of phlogopite and carbonate (both dolomite and calcite), along with small (<50 um) grains of perovskite, chromite, apatite, ilmenite, and minor rutile.

The xenoliths found in the Six Mile Creek dikes vary from garnet pyroxenites to plagioclase and spinel bearing lherzolites, to calcareous shales, indicating that the kimberlitic magma sampled material from various depths in the mantle and crust during emplacement.

	SMC	TC	WB
Macrocrysts			
Olivine	**A**	**A**	**A**
Phlogopite	**A**	**A**	**P**
Garnet	**C**	**C**	
Clinopyroxene	**C**	**C**	**P***
Orthopyroxene	**P**		**P***
Spinel	**C**	**C**	
Chromite	**C**	**C**	
Matrix Phases			
Serpentine	**A**	**C**	**A**
Calcite	**C**	**A**	**C**
Dolomite	**C**		
Phlogopite	**A**	**C**	**A**
Clinopyroxene	**P**		**P**
Unidentified Ca-Fe Silicate			**P**
Perovskite	**P**	**P**	**C**
Ilmenite	**P**		**P**
Rutile	**P**		
Magnetite / Chromite	**C**	**C**	**C**
Apatite	**P**	**P**	**C**
Fe Sulfides and /or Fe-Ni Sulfides	**P**	**P**	
Barite / Celestine		**P**	

Table 2. Mineral phases observed in the Six Mile Creek (SMC), Taughannock Creek (TC), and Williams Brook (WB) kimberlite dikes. A = Abundant (>10%); C = Common (1-10%); P = Present (<1%); Blank = not observed; (*) = only in xenoliths.

Figure 8. Clinopyroxene, phlogopite, and serpentinized olivine macrocrysts in the Six Mile Creek kimberlite (sample SMC-2A, PPL).

Figure 9. Garnet pyroxenite xenolith in Six Mile Creek dike. Xenolith is composed of pyrope garnet (colorless), clinopyroxene (pale green), chromite (black), and amphibole (pale brown) (sample SMC-2A, PPL).

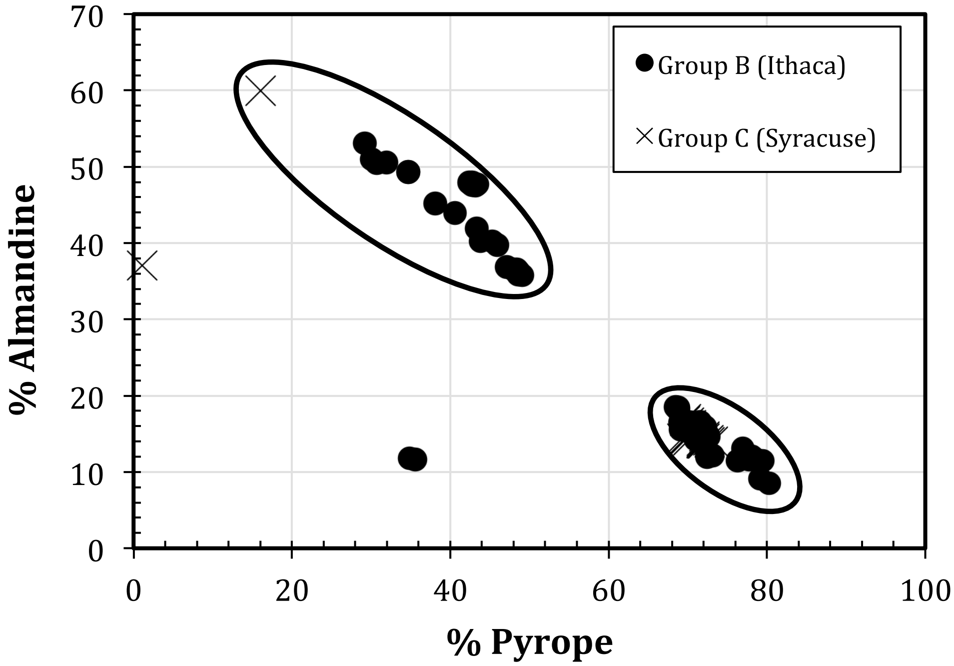


Figure 10. Garnet macrocryst compositions in New York State kimberlites.

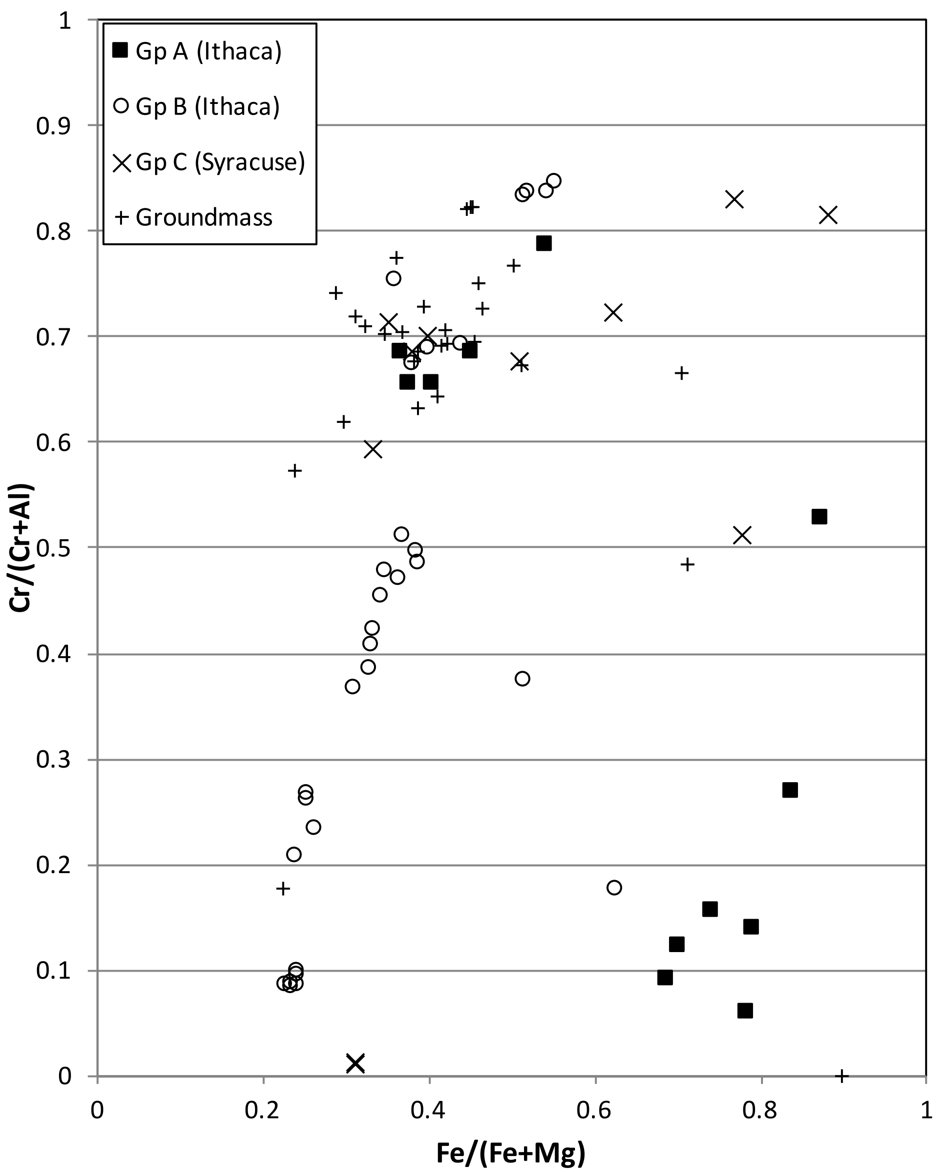


Figure 11. Molar Cr/(Cr+Al) vs. Fe/(Fe+Mg) ratios in spinel grains in New York State kimberlites.

STOP #2: Williams Brook

Parking Location and Coordinates: Small gravel turn out on west side of NY Route 96 just after turn for Hopkins Place (42.45706, -76.52462).

Just to the north of the turn out, Route 96 crosses over a small creek. Enter the creek on the west side of the road, and hike upstream for ~ 60 m. The Williams Brook kimberlite is a dark green-black dike approximately 3.5 m wide; it is best exposed on the northern bank of the creek.

History of the Williams Brook Dike

Despite being one of the largest dikes in the region, the Williams Brook dike wasn't recognized until the late 1930s, probably being first exposed by the extreme flooding that occurred in the region in July 1935 (Johnson, 1936). Filmer (1939) was the first to record the location and size of the dike; no other studies were done on the dike until a paleomagnetic study was done by a Cornell undergraduate in 1970 (DeJournett, 1970). The results of DeJournett's work indicated that the Williams Brook dike exhibited normal magnetic polarization with a pole position "reasonably consistent" with a Lower Cretaceous age of emplacement (DeJournett and Schmidt, 1975). Subsequent paleomagnetic studies of the Williams Brook and other kimberlites in the Ithaca region, however, indicated a Lower Cretaceous pole position that was not consistent with currently accepted Upper Jurassic to Lower Cretaceous pole positions for North America (Van Fossen and Kent, 1991, 1993). The interpretation of the magnetic characteristics of kimberlitic rocks is complicated by the fact that the duration of magnetization acquisition is protracted, probably occurring during serpentization following emplacement.

Basu et. al (1984) were the first to try to date the Williams Brook dike; they obtained a whole-rock K-Ar age of 139 ± 7 Ma. Because of uncertainties in how xenocrystic phlogopite and post-emplacement serpentinization impact K-Ar systematics, recent U-Pb dates obtained on groundmass perovskite grains are thought to more accurately record emplacement ages. Heaman & Kjarsgaard (2000) dated two multi-grain perovskite samples from the Williams Brook dike and obtained ages of 144.8 ± 3.2 and 146.7 ± 2.4 Ma, with a weighted average emplacement age of 146.0 ± 1.9 Ma.

Kay and Foster (1986) noted that the Williams Brook dike was petrographically distinct from most of the other dikes in the Ithaca region, containing significantly more serpentine and phlogopite, and less calcite, and lacking distinct macrocrysts of garnet, spinel, or pyroxene. These features are, in fact, shared by all of the "Group A" kimberlites, along with the presence of abundant perovskite in the matrix. The only chemical data reported for the Williams Brook dike noted its high incompatible element concentrations, and steep REE profile (Kay, 1990).

Petrography of the Williams Brook dike

The Williams Brook dike, and all Group A intrusions, are dense, dark-colored, rocks that are relatively resistant to weathering and erosion. The Williams Brook dike is fine-grained and relatively homogenous across its width; the only distinct crystalline phase visible in hand sample is phlogopite. Small (< 1cm wide) calcite-filled veins are common near the margins of the dike, probably representing cooling joints that were filled by carbonate derived from the surrounding sedimentary rocks.

In thin section, the dike is characterized by large olivine macrocrysts (up to 4 mm in diameter) that are partly to completely replaced by serpentine and magnetite (Figure 12). Electron microprobe analysis of the olivine revealed that they are relatively uniform in composition (~$Fo_{90.5}$).

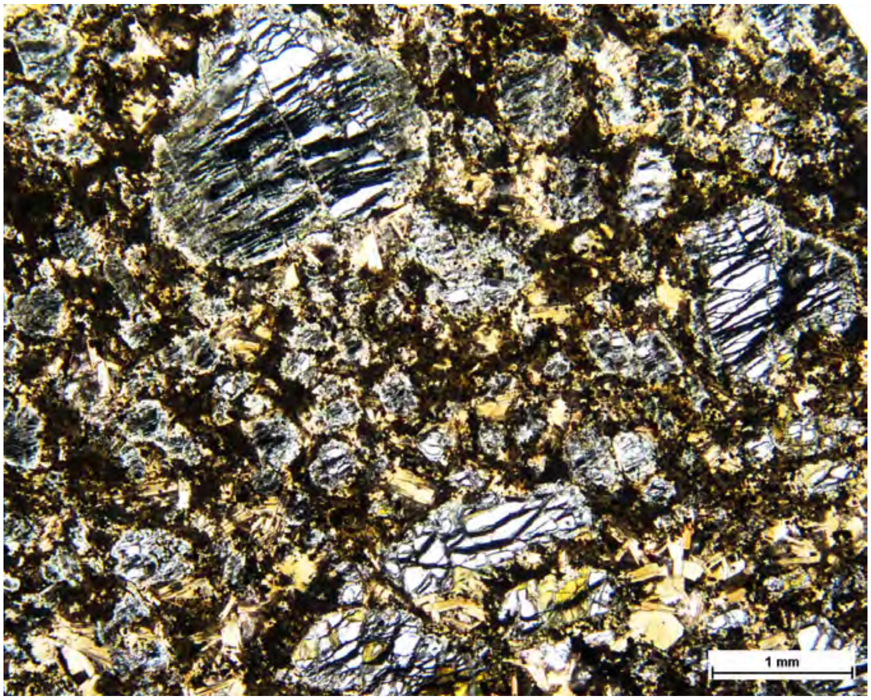


Figure 12. Photomicrograph of Williams Brook dike showing large olivine macrocrysts replaced by serpentine and magnetite (top left, right center) in a matrix of phlogopite, serpentine, calcite, magnetite, and perovskite (Sample W2; PPL).

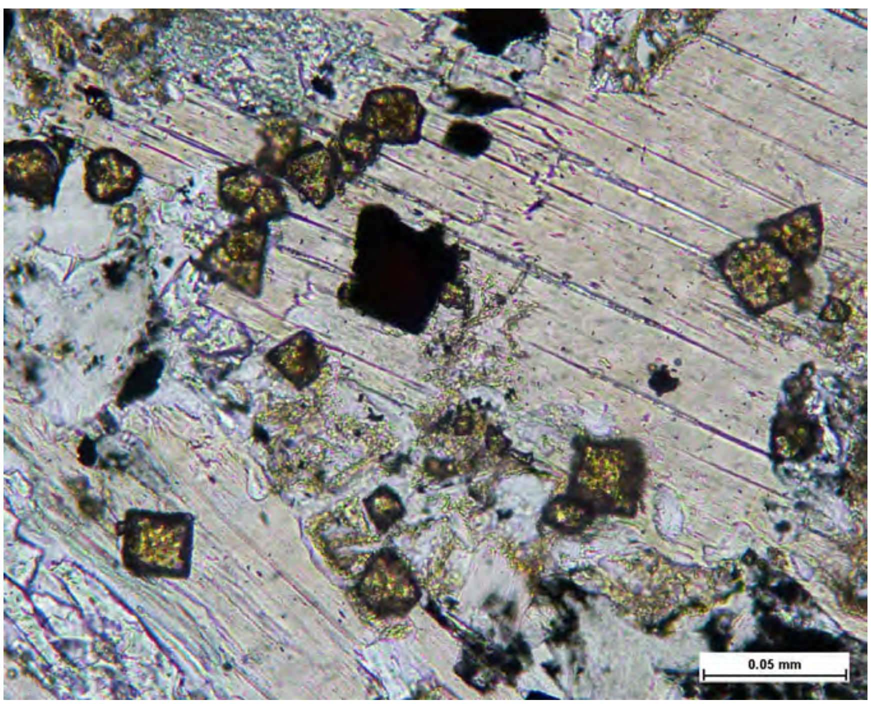


Figure 13. Photomicrograph of the matrix of the Williams Brook dike showing tabular phlogopite (pale orange), calcite (colorless, high relief), serpentine (pale green), perovskite (yellow-brown, high relief), and magnetite (opaque) (Sample W2; PPL).

Petrography of the Williams Brook dike (cont.)

While the Williams Brook dike contains abundant phlogopite in the groundmass, distinct phlogopite macrocrysts are not common. Electron microprobe and SEM/EDS analyses of the phlogopite grains reveal that they are compositionally similar to phlogopites found in the both the Group A and Group B kimberlites, with average FeO and TiO_2 concentrations of ~ 7 and 2.5 wt. %, respectively. Small amounts of barium are also present, particularly in the groundmass grains.

No other macrocryst phases were observed, and only one distinct xenolith was found. The xenolith had a maximum dimension of ~ 2 cm, and consisted of a coarse-grained aggregate of partly serpentized olivine with a few grains of bright green, Cr-bearing diopside, and pale tan enstatite (Figure 14).

The groundmass contains abundant phlogopite, and considerably less carbonate relative to Group B intrusions. The most distinguishing feature of the Williams Brook dike and related Group A intrusions exposed along the western margin of Cayuga Lake are the abundant, unaltered, relatively large (up to 75 μm diameter), euhedral perovskite grains in the groundmass (Figure 13). The abundant perovskite reflects the high TiO_2 concentrations in these intrusions (2.75 to 4.0 wt. %), and is what allowed them to be accurately dated (Heaman and Kjarsgaard, 2000). The only other New York kimberlites with high TiO_2 concentrations are the two dikes exposed along East Canada Creek (Group D intrusions). Unfortunately, the groundmass perovskite grains in these dikes have been largely replaced by rutile and a mixture of unidentified oxides and titanates.

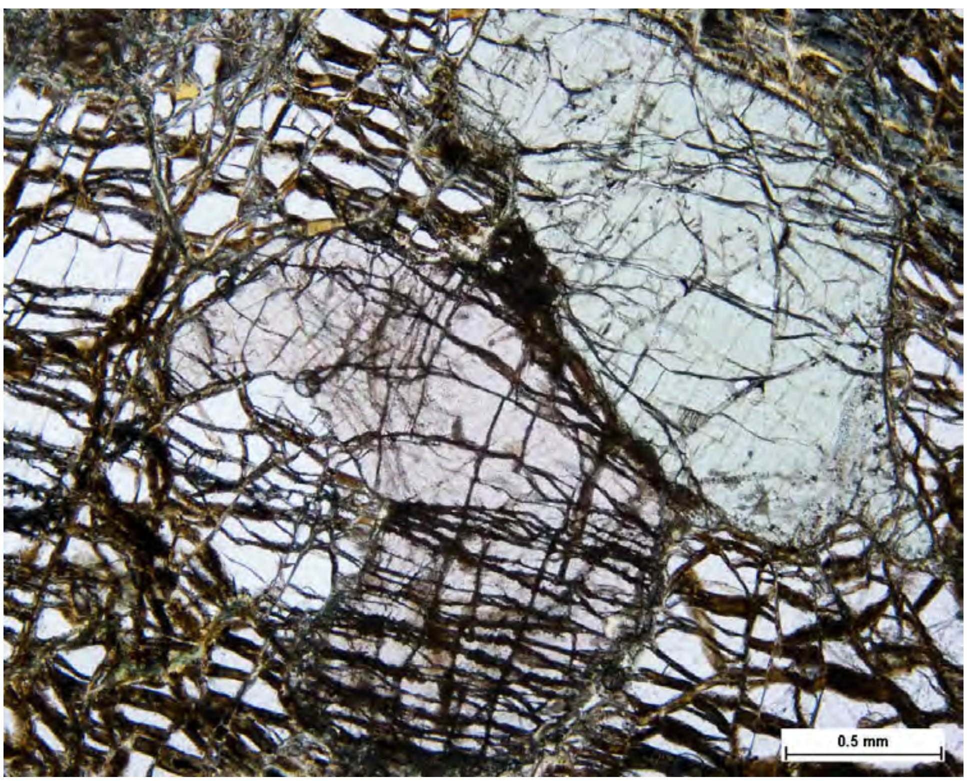


Figure 14. Photomicrograph of peridotite xenolith in Williams Brook dike. Pale green diopside (upper right), pale tan enstatite (bottom center), and olivine (colorless, with abundant serpentine along fractures). (Sample WB Inc; PPL).

STOP #3: Taughannock Creek

Parking Location and Coordinates: Small gravel turn out on south side of Taughannock Park Rd. (County Rd. 148A) (42.53054, -76.62116).

Take the short fishing access path to the nicely exposed rocks on the banks of Taughannock Creek. A total of 15 individual dikes, in five clusters, have been reported from a 1.5 km long section of Taughannock Creek (Figure 15) (Foster, 1970; Martens, 1924; Matson, 1905). Due to erosion and revegetation along the banks of the creek, few of these dikes are currently exposed. We will try to find two of the westernmost dikes in Taughannock Creek. NOTE: All of the dikes are within the confines of Taughannock Creek State Park, and sample collecting is prohibited.

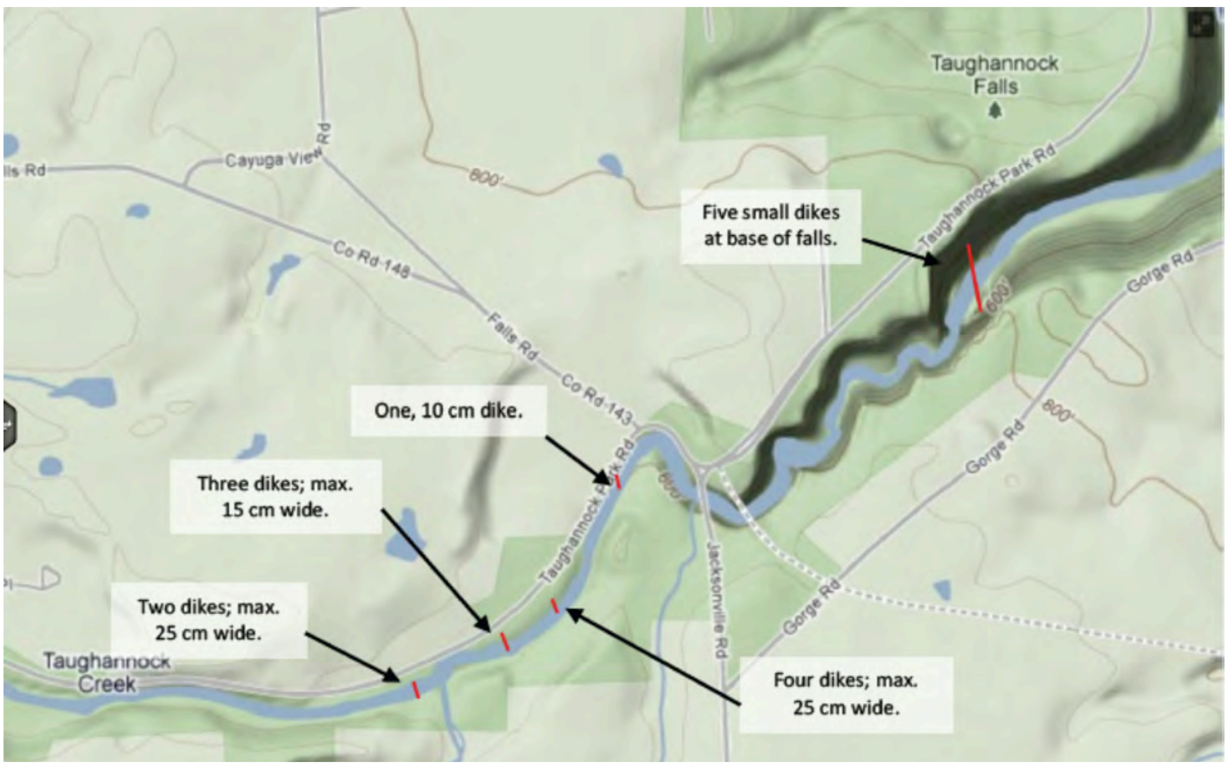


Figure 15. Approximate locations along Taughannock Creek where a total of 15 small dikes have been reported. Few are currently exposed. Modified after Foster (1970), Figure 1, p.10.

History of the Taughannock Creek Dikes

The first report of dikes exposed along Taughannock Creek was by Matson (1905) in which he described five dikes, all less than 10 cm in width, being exposed in the south wall of the gorge below Taughannock Falls, and one dike, < 5 cm wide, being exposed ~ 1 km upstream. He also noted that a thrust along a bedding plane offset the dikes exposed in the wall of the gorge by ~ 50 cm. Martens (1924) discovered one of the ~25 cm wide dikes upstream of the falls, and Foster (1970) identified and described a total of ten dikes in the section of Taughannock Creek above the high falls. Most of the dikes are < 5 cm wide, and most pinch out rapidly along strike. The lack of severe flooding in the region over the past 50 years has allowed sediment and vegetation to obscure most of these small, easily weathered dikes.

A number of petrological studies of the Taughannock Creek dikes were done in the 1980s (Jackson, 1982; Jackson et al., 1982a, b; Kay et al., 1983; Snedden, 1983; Snedden and Kay, 1981b). These were the first studies to document the multiple populations of garnet, clinopyroxene, and spinel macrocrysts that occur in these dikes, and to conclude that most are xenocrysts derived from two dominant sources: the first a shallow (< 100 km), relatively undepleted mantle peridotite, and the second a granulite facies, mafic lower crust (Kay et al., 1983). Pressure and temperature estimates of equilibration for the mantle macrocryst suite range from 28-32kb and 1020-1070^{o}C (Jackson et al., 1982a) to 15-20 kb and 850-880^{o}C (Kay et al., 1983).

Petrography of Taughannock Creek dikes

As first noted by Foster (1970), the dikes exposed along Taughannock Creek are quite variable in both hand-sample and in thin section. Overall color, texture, style of weathering, and relative abundance of macrocryst phases varies considerably from dike to dike (Figure 16). The characteristics that they share, and that define Group B intrusions, are the relative abundance of calcite in the matrix and, in addition to olivine, the presence of one or more of the following phases as macrocrysts: phlogopite, pyrope garnet, Cr-bearing diopside, and/or spinel.

Figure 16. A) Taughannock Creek dike filling N-S oriented fracture, with highly weathered chilled margins (hammer length = 33 cm). B) Polished slab of Taughannock Creek dike showing large, rounded, serpentinized olivine macrocrysts and rounded pyrope macrocryst w/ keliphytic reaction rim (width of photo = 2 mm).

Petrography of Taughannock Creek dikes (cont.)

Olivine was a common macrocryst and matrix phase in all of the Taughannock Creek dikes, but has been completely replaced by serpentine, calcite, and/or magnetite; no fresh olivine has been found in any of the specimens examined to date. In most dikes, the large olivine macrocrysts are rounded, suggesting a xenocrystic origin, however, in one dike many of the pseudomorphs retain euhedral olivine morphologies, suggesting some may have been phenocrysts in equilibrium with the host magma (Figure 17).

Phlogopite is the second most abundant macrocryst, and most of the larger grains are strongly zoned and rounded (Figure 18). Compositionally, the phlogopite macrocrysts are similar to those in other New York State kimberlites, containing up to 3 wt. % TiO_2, and 5 to 8 wt. % FeO. In many samples, the small tabular matrix grains are strongly flow-aligned.

Clinopyroxene macrocrysts are relatively common; most are < 1mm in diameter, are bright green in hand sample and colorless in thin section. Unlike the clinopyroxene macrocrysts in the Six Mile Creek dikes (Figure 7), these grains are homogeneous and do not exhibit pronounced compositional zonation. As noted by Jackson et al. (1982b) most of the grains are Cr-bearing diopsides containing 1 to 1.5 wt. % Cr_2O_3; a smaller population of Cr-poor, Al-rich diopside macrocrysts is also present.

Orthopyroxene macrocrysts were reported by Jackson et al. (1982a), but have not been observed by the authors.

Garnet macrocrysts are present in most of the Taughannock Creek dikes, but in low concentrations. Grains picked out from heavy mineral separates vary in color from pale orange to deep purple. Most grains are highly fractured and rounded, with a well-developed reaction rim (Figure 14). Three populations of garnet grains have been documented: 1) Cr-bearing pyrope (1.5 to 4.5 wt. % Cr_2O_3); 2) high-Ca pyrope-almandine; and 3) low-Ca pyrope-almandine (Figure 19). Jackson et al. (1982a) recognized the presence of both pyrope and almandine-rich garnets in the Taughannock Creek kimberlites, and attributed the pyrope garnet (and Cr-bearing diopside) macrocrysts to a shallow, upper mantle source, and the almandine-rich garnets (and Cr-poor diopside) macrocrysts to a lower crustal, eclogitic source.

Spinel macrocrysts are common; in thin section they are always anhedral, rounded, and embayed, and range in color from pale tan to dark brown, red-brown, olive green and opaque. Compositionally, spinel macrocrysts from the Group B kimberlites in the Ithaca region are the most diverse, ranging from near end-member chromite to near end-member spinel (Figure 11).

The groundmass of Group B kimberlite dikes is dominated by carbonate, serpentine and phlogopite, but in widely varying proportions between intrusions. Perovskite is also present in the matrix, but typically only as very small (< 20 µm diameter), partly altered grains, making them unsuitable for U-Pb dating. Magnetite and apatite are the only other phases commonly observed in the groundmass of Group B intrusions.

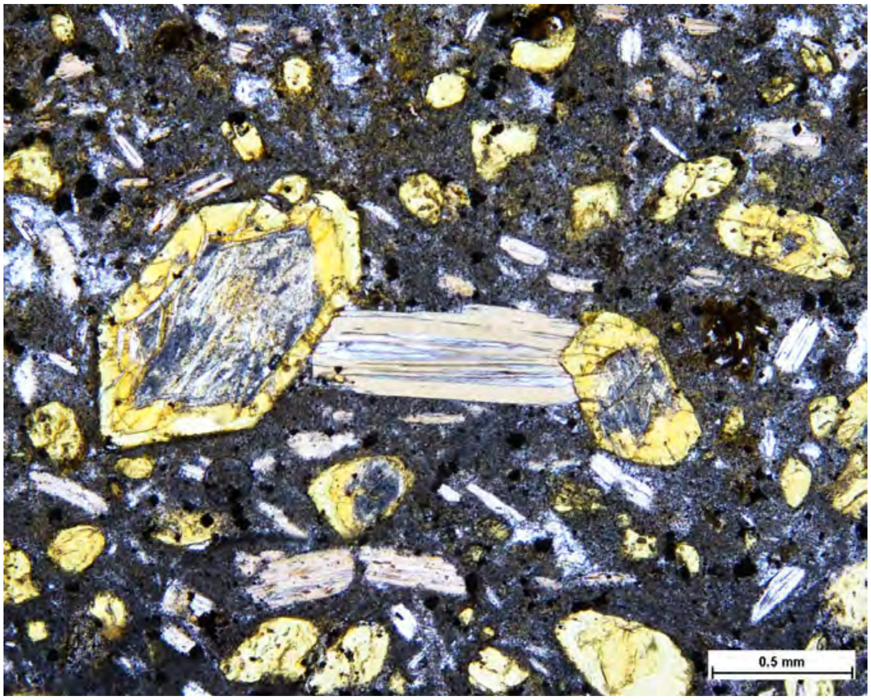


Figure 17. Photomicrograph of Taughannock Creek dike showing partly serpentized phlogopite macrocrysts (pale tan), and large euhedral olivine phenocrysts (pseudomorphed by serpentine, calcite, and magnetite) (Sample TC-3; PPL).

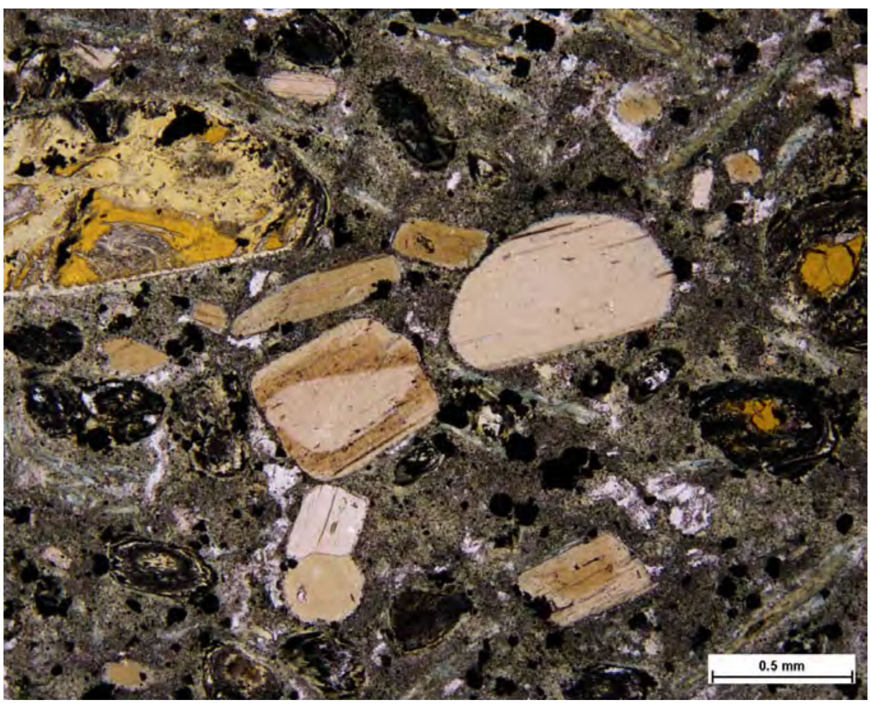


Figure 18. Photomicrograph of Taughannock Creek dike showing rounded, zoned, phlogopite macrocrysts (pale tan to brown), and large olivine macrocrysts (pseudomorphed by serpentine and magnetite) (Sample TC-1; PPL).

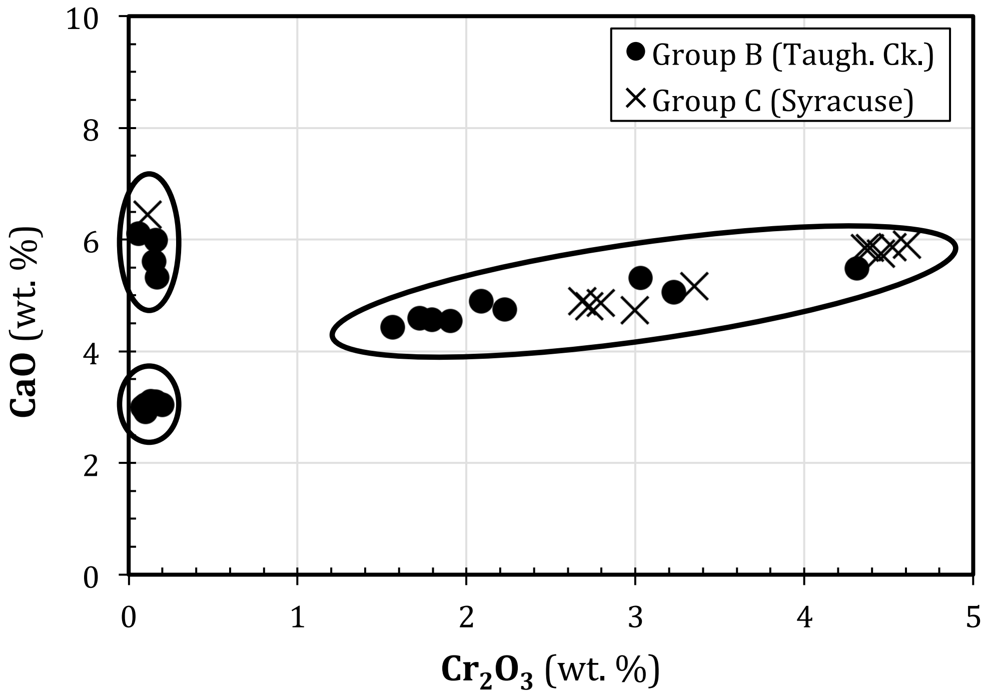


Figure 19. Compositions of garnet macrocrysts in Taughannock Creek dikes and the Dewitt Reservoir diatreme. (Data from O'Sullivan (2017) and Bailey (unpublished)).

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