Geology of the Copper-Kiln Landslide: a glimpse into the Marcy massif detachment zone

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INTRODUCTION

The Mesoproterozoic Grenville Province of eastern North America is a classic Proterozoic orogenic belt that formed over a protracted period resulting in the assembly of Rodinia (Hoffman, 1988). Despite the routine interpretation that the Grenville Province exposes the orogenic infrastructure of modern collisional orogens, the Grenville is unique from Phanerozoic orogenic belts, as anorthosite and related mafic rocks comprise >20% of the exposed region (Fig. 1a; Corriveau et al., 2007). This is in stark contrast to all Phanerozoic orogens, which lack massif-type anorthosite, let alone in such quantities or volumes (Ashwal, 1994; 2010). Owing to a high rheologic strength resulting from exceptionally coarse grain sizes, high temperatures of crystallization, and relatively low density, it follows that anorthosite complexes may have had a profound impact on the thermal and structural architecture of the Grenville Province as a whole.

The Adirondack Mountains in northern New York are a Mesozoic domical uplift of Grenvillian basement and form the southern extension of the contiguous Grenville Province (Fig. 1b; Roden-Tice et al., 2000). The region has served as a testing ground for petrologic inquiry and new analytical techniques for decades (Kemp, 1898; Buddington, 1939; Postel, 1954; Valley and O'Neil, 1982; Bohlen, 1985; Spear and Markussen, 1997; Bonamici et al., 2015; Quinn et al., 2017; among many others). The Adirondack Mountains contain several anorthosite complexes including the Marcy massif, the Oregon dome, and Snowy Mountain dome. The Marcy anorthosite massif (Mm) is a 3000 km^2 classic Proterozoic-type anorthosite complex underlying the majority of the High Peaks region of the Adirondack Park in northern NY, and is thus an excellent place to study the impact of volumetrically abundant anorthosite on the orogenic infrastructure of the Grenville Province.

In late August, 2011, Tropical Storm Irene catalyzed over 40 landslides in the High Peaks region (Mackenzie, 2017). The highest concentration of landslides occurred within the eastern High Peaks area, and provide an unprecedented window into the internal compositional heterogeneity and structural complexity within the relatively undeformed Marcy massif (Chiarenzelli et al., 2015). As a companion to a 2015 NYSGA field trip (Chiarenzelli et al., 2015), which focused on the Bennies Brook slide on the northwestern slope of Lower Wolfjaw Mountain, we looked at a landslide in proximity to the northern margin of the Marcy massif. The Copper-Kiln (or Cooper-Kill) landslide occurred north of Wilmington near Whiteface Mountain, and combined with detailed 1:24,000-scale mapping along the southeastern margin of the Marcy massif, provide insight into how the anorthosite behaved during the polyphase metamorphic and structural evolution of the Adirondack Mountains.

BACKGROUND

The Grenville Province of North America records evidence for multiple accretionary phases followed by a collisional tectonic phase lasting from 1080 – 980 Ma referred to as the Grenvillian Orogeny (Rivers, 2008). The Adirondack region dominantly formed during the Shawinigan orogeny, which ended with extensive Anorthosite-Mangerite-Charnockite-Granite (AMCG) plutonism (McLelland et al., 2004). The Adirondack region is divided into the amphibolite-facies Adirondack lowlands and granulite-facies Adirondack highlands (Fig 1b; Selleck et al., 2005). Separated by the southwest-striking, northwest-dipping, Carthage-Colton shear zone, the Adirondack highlands preserve evidence for experiencing granulite-facies metamorphism during the Ottawan phase of the Grenvillian Orogeny (*referred to as Ottawan orogeny here;* McLelland et al., 2001), which is absent in the adjacent

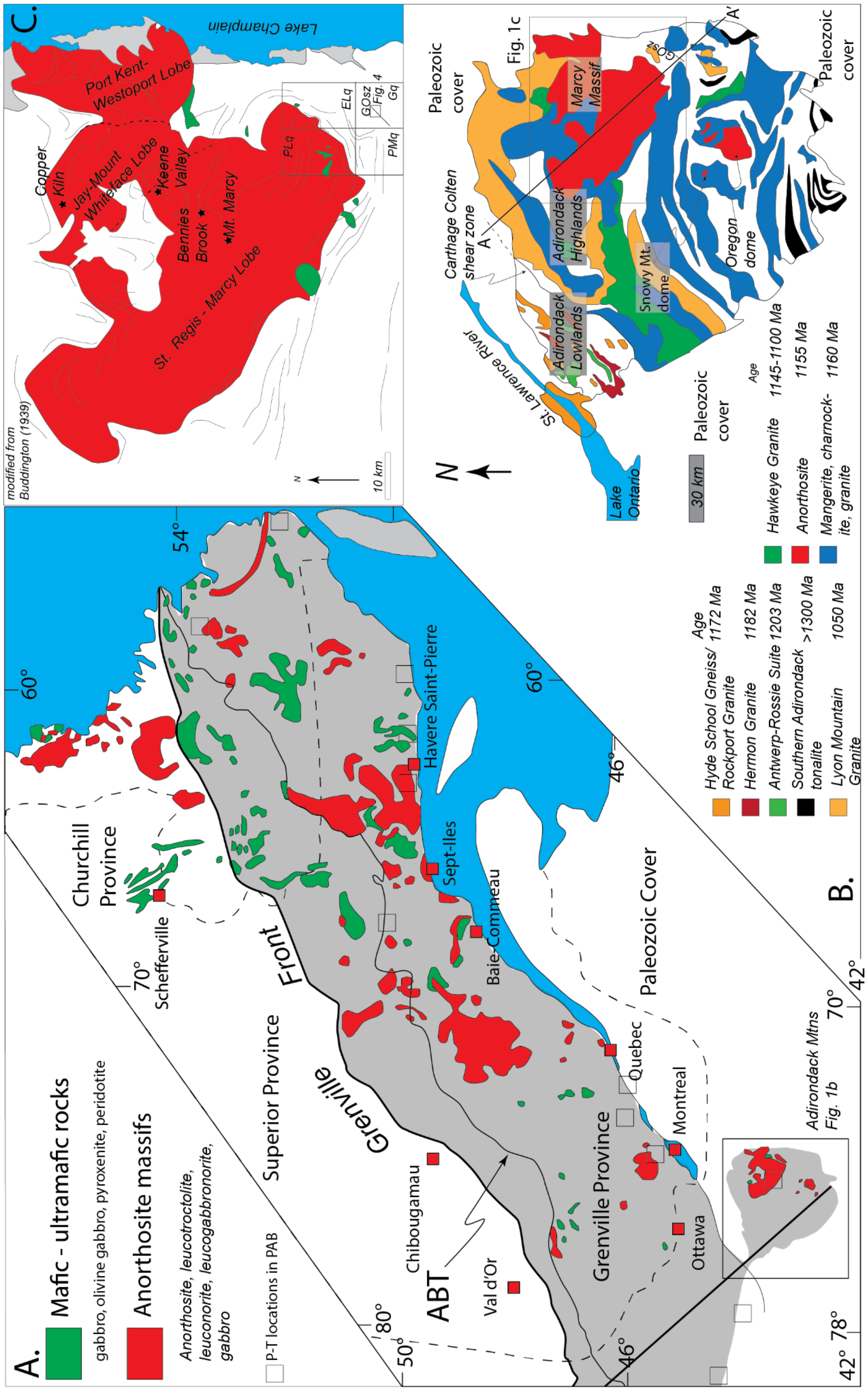


Figure 1: A) Schematic map of the Mesoproterozoic Grenville Province showing the distribution of massif-type anorthosite bodies (ABT: allochthon boundary thrust; modified from Corriveau, 2007); B) Generalized geologic map of the Adirondack region displaying the distribution of igneous suites (modified from McLelland et al., 2004); C) Detailed map of the Mm with foliation form lines from Balk (1931; modified by Buddington, 1939) – Location of Copper-Kiln slide on *northwestern margin of the Jay-Mt Whiteface lobe*.

lowlands. Structural and geochronologic data from the Carthage Colton shear zone indicate that it accommodated top down to the northwest (normal) motion juxtaposing orogenic lid rocks too high in the crust to have undergone regional penetrative tectonism during the Ottawan phase of the Grenville Orogeny adjacent to middle crustal rocks of the Adirondack highlands (Selleck et al., 2005; Bonamici et al., 2011; 2015). Motion along the Carthage Colton shear zone occurred at ca. 1040 Ma, interpreted to reflect collapse of overthickened crust at the end of the Ottawan orogeny (Selleck et al., 2005).

Evidence for extensional collapse in the Adirondack Mountains is widespread and been the focus of substantial work. The Carthage-Colton shear zone is the best studied feature exhibiting extensional deformation and delineates the boundary between Adirondack highlands and lowlands (Selleck et al., 2005). The East Adirondack shear zone to the south and east of the Marcy massif is also interpreted to reflect orogenic collapse and accommodated top – down to the southeast deformation at ca. 1040-1020 Ma (Wong et al., 2011). However, this feature has only been identified in several road outcroppings, and it does not correspond to a major thermal discontinuity as does the Carthage-Colton shear zone. Also associated with extensional collapse is the voluminous emplacement and crystallization of leucogranitic to syenitic rocks collectively referred to as the Lyon Mountain granite (LMG; Postel, 1954; Chiarenzelli et al., 2017). The LMG rims the Marcy massif and intruded along mylonitic zones in the Carthage Colton shear zone (Selleck et al., 2005). It is undeformed and cross cuts regional granulite-facies tectonic fabrics, providing a minimum age of tectonism. Decades of detailed U-Pb zircon geochronology has confirmed late Ottawan emplacement of the LMG, with U-Pb zircon crystallization ages of individual samples spanning from 1062 – 1038 Ma (Chiarenzelli et al., 2017; *and references therein*). Of particular interest are numerous iron oxide-apatite deposits hosted by the Lyon Mountain granite, which have a controversial origin ranging from completely magmatic (Lupulsecu et al., 2017) to entirely metasomatic (Valley et al., 2009; 2011). The degree of albitization associated with all ore occurrences demands a metasomatic component, but the role and origin of fluids in concentrating ore materials in the LMG remains enigmatic.

Petrogenesis of the Adirondack AMCG suite

Within the Adirondack highlands, the largest suite of plutonic rocks belong to the ca. 1160-1140 Ma anorthosite-mangerite-charnockite-granite (AMCG) suite (Fig. 1b; McLelland et al., 2004; Hamilton et al., 2004), which are, collectively, a hallmark of the Grenville Province and Proterozoic anorthosite complexes as a whole. Zircon geochronology (McLelland et al., 2004) suggests that members of this suite are coeval, but not necessarily comagmatic, in which anorthosite and mafic varieties of the suite are derived from fractional crystallization of asthenospheric-derived mafic parent (Regan et al., 2011), and quartz-bearing endmembers are derived from lower crustal anatexis (McLelland et al., 2004; Hamilton et al., 2004). Furthermore, based on timing constraints, anorthosite, and associated MCG, magmatism corresponds to the final stages of Shawinigan orogenesis, which set the stage for lithospheric foundering and asthenospheric upwelling catalyzing the formation of anorthosite at the base of the crust (Valentino et al., 2018).

The AMCG suite of the Adirondack region has been host to numerous stable and radiogenic isotopic tracer studies, including Oxygen in zircon (Valley et al., 19934); Hafnium in zircon (Bickford et al., 2010); Oxygen in contact zone minerals (Valley and O'Neil, 1982), and Oxygen in plagioclase feldspar (Morrison and Valley, 1989; Peck et al., 2010a), and whole rock separates (Peck et al., 2010). Oxygen isotopes in zircon display uniformly elevated δO^{18} values from 8.0 – 11.0 ‰ (Valley et al., 1993; Peck et al., 2010a). Values for AMCG rocks in the Adirondack Mountains are anomalously high compared to most other AMCG suites in the Grenville, except for the Morin Massif, which preserves similarly high δO^{18} values (Peck et al., 2010a). The deviations of these two complexes were preliminarily interpreted as having been contaminated by oceanic lithosphere, in contrast to other anorthosite massifs (Peck et al., 2010a). Furthermore, Hf isotopic measurements in zircon display uniform $\varepsilon_{Hf(Tc)}$ (Tc = time of crystallization) throughout the entire suite, which plot between contemporaneous CHUR (chondritic uniform reservoir) and depleted mantle (Bickford et al., 2010). Therefore, much of the isotopic characteristics of the Mm are analytically identical to those of coeval granitoid rocks, which may be a function of relatively low residence time of granitic source rocks (Peck et al., 2010a).

A suite of gabbronorite rocks, commonly referred to as coronitic metagabbros, occur as satellite plutons exposed along the edges of the Mm (Buddington, 1939; McLelland and Chiarenzelli, 1988; McLelland et al., 2004; Regan et al., 2011), with a minority internal to it, and share a similar U-Pb crystallization age (McLelland and Chiarenzelli, 1988; McLelland et al., 2004). They contain a higher $\varepsilon_{Nd(Tc)}$ than the surrounding Mm (Regan et al., 2011), and mantle like δO^{18} values (6.0 ‰; Valley et al., 1993), suggesting that they did not undergo the contamination present within the Mm. Whole rock major and trace element geochemistry and Nd isotopic evidence was discussed in Regan et al. (2011) and demonstrates that the suite of gabbronorites is permissible as the parental magma for the Mm. These data collectively suggest that the Mm experienced hybridization and batholith-wide contamination by and with the granitoid counterparts during or after the parental magma had become isotopically isolated.

Constraints on metamorphism in the Adirondack highlands

The Adirondack highlands have been host to classic thermobarometric studies (Bohlen et al., 1985) and forward petrologic modelling (Spear and Markussen, 1997; Storm and Spear, 2005). However, until recently, distinguishing effects of Shawinigan vs Ottawan orogenies remained problematic. Initially, based on exchange thermometry, Bohlen et al (1985) suggested that paleoisotherms were centered on the Marcy anorthosite massif and Oregon Dome (Fig. 1b), which also corresponded to zircon recrystallization textures above the 725°C paleoisotherm (Chiarenzelli et al., 1993). Spear and Markussen (1997) performed systematic thermobarometric analysis and petrogenetic modelling on anorthositic rocks from the northern Marcy massif, and acquired peak P-T conditions of 0.8 GPa and > 800°C corresponding to garnet-absent pyroxene recrystallization, followed by cooling and exhumation. Storm and Spear (2005) performed a similar analysis on a suite of metapelitic rocks in the southern Adirondack Mountains, which yielded similar P-T results interpreted by the authors to suggest that the "bulls-eye" pattern of Bohlen et al (1985) was not a robust estimate of peak temperatures.

In-situ zircon geochronology from anorthosite-series rocks was performed and presented in Peck et al. (in press). Samples were acquired from the southeastern margin of the Mm, but similar petrologic textures were observed in a suite of samples from the northern margin of the Mm presented in Spear and Markussen (1997). Zircon associated with garnet coronae around ilmenite were targeted as the ilmenite would provide Zr during retrograde metamorphism from a garnet-absent peak assemblage (Spear and Markussen, 1997; Peck et al., in press). Analyses suggested coronae growth, which post dates deformation in most places, occurred from ca. 1060 – 1040 Ma, overlapping considerably with the emplacement of the Lyon Mountain granite (Chiarenzelli et al., 2017). In-situ zircon dating from a suite a quartzites near the sample locality of Storm and Spear (2005) was performed by Peck et al. (2010). Their study indicates that local anatexis and metamorphic zircon growth occurred at c. 1180-1135 Ma, synchronous with the Shawinigan Orogeny (Peck et al., 2010b). Therefore, although the thermobarometric constraints suggest similar peak metamorphic conditions across the Adirondack highlands, ambiguity remains over the timing of P-T conditions retrieved from any rock sample in the absence of robust petrochronologic constraints, . It is clear that AMCG rocks near the Marcy massif underwent granulite-facies metamorphism during the Ottawan orogeny. However, these data also suggest that the "bulls-eye" pattern (Bohlen et al., 1985) may represent Ottawan paleoisotherms, and that conditions calculated by Storm and Spear (2005) represent Shawinigan conditions overprinted by an Ottawan thermal disturbance.

The Marcy massif: a historic perspective

The Adirondack anorthosites have been studied for over a century (Kemp, 1898; Ailling, 1932). Although rocks belonging to the series are highly variable in texture and composition, they are generally lumped into two separate units, or facies (Kemp, 1898; Buddington, 1939). The Whiteface-facies is predominately composed of gabbroic anorthosite to anorthositic gabbro and fine to medium-grained anorthosite and other intrusive units like jotunites, ferrodiorites, and gabbros. The Marcy-facies (or megacrystic Anorthosite) is composed of coarse to pegmatitic anorthosite with blue-gray andesine and subordinate labradorite (Miller, 1919). Composition and grain size aside, the most obvious differences between the two facies are the spatial distribution and degree of deformation of each unit. The relatively finer-grained Whiteface-facies is generally found at or near the margin of the Marcy Anorthosite massif and commonly contains a strong protomylonitic to mylonitic fabric. This was originally interpreted as a km-scale chill zone around the core of Marcy-facies Anorthosite (Kemp, 1898). This idea has not been developed or rigorously tested, but is the best model to explain the spatial variations in anorthosite texture. The contact between the two facies is gradual, and often composed of interlayered rock with characteristics of each, referred to as the "transitional zone" by Buddington (1939).

Buddington (1939; after Balk, 1931) separated the Mm into three lobes (Fig. 1c): the St. Regis- Marcy (Cushing, 1907; Ailling, 1919; Balk, 1931), the Jay-Mount Whiteface (Buddington, 1939), and the Port-Kent – Westport (Balk, 1931; Buddington, 1939). Fig. 1c is modified from Buddington (1939; after Balk, 1931). Each lobe has a Marcy-facies core wrapped by deformed Whiteface-facies, indicating that the three may be three distinct structural domes of the same batholith. Tectonites, including the heterogeneous Whiteface-facies, parallel the margin of the Mm (Balk, 1931) suggesting that rocks deformed around the Mm during regional deformation and metamorphism. Based on in-situ zircon geochronology, the age of this phase of tectonism is interpreted to be c. 70 Ma younger than the crystallization of the Mm and related rocks (Peck et al., in press).

The emplacement mechanism of the Mm and massif-type anorthosite in general remains the subject of debate (Meyers et al., 2008). One of the foundational problems central to this debate is the emplacement depth of massif-type anorthosite. Petrologic evidence for a polybaric origin for the Mm is widespread. High Al opx megacrysts suggest crystallization over 1.0 GPa (Bohlen and Essene, 1978). However, the presence of monticellite and depleted δO^{18} values within the contact zone of the Mm require a shallower emplacement depth (Valley and O'Neil, 1982; Clechenko et al., 2002), consistent with orthopyroxene compositions from Marcy-facies anorthosite (Spear and Markussen, 1997). However, within extensional settings, meteoric water has been demonstrated to be capable of penetrating depths > 20 km. Florence et al. (1995) interpreted moderate pressure and high temperature metamorphism (P: 0.37 – 0.64 GPa and T: 700°-770°C) within the western Adirondack Mountains to have been synchronous with AMCG magmatism based on macro and microstructural relationships with proximal nelsonite dikes.

STRUCTURE OF THE MARCY MASSIF

The Mm exhibits vastly different deformation styles from its interior to its margins. The following section describes the structures within the Mm, at the margins of the Mm, the differences between them, and their implications for the deformational history of the Mm.

Deformation within the Marcy massif

The Mm is a vast region of undeformed, coarse-grained to pegmatitic anorthosite. However, parts of the interior Mm preserve evidence for localized deformation in the form of cm-scale granulite to amphibolite-facies shear zones, often corresponding to rheologic heterogeneities (Chiarenzelli et al., 2015). Detailed structural work on the Bennies and Wolfjaw Brook landslides will be described in detail here, but similar features have been observed in other locations throughout the Mm, including Cascade, Big Slide, Saddleback, Algonquin, Wright, and Hurricane Mountains. For more information on the Bennies Brook landslide please refer to Chiarenzelli et al. (2015), but detailed descriptions of other landslides are currently unavailable.

The reactivated Bennies Brook landslide formed during Tropical Storm Irene in 2011. It is positioned on the northwest slope of Lower Wolfjaw Mountain (Mackenzie, 2017). There are predominately two orientations of shearing exposed along the landslide with variable, but broadly consistent shear sense (Fig. 2). Both sets of shear zones are (sub)vertical with weakly developed subhorizontal mineral stretching lineations. Typically, NNW-SSE oriented shear zones contain dextral kinematic indicators and ESE-WNW oriented shear zones display a sinistral shear sense. Where seen interacting, the two generations of shear zones are mutually off-setting, suggesting a conjugate origin. A small set of pegmatitic gabbro dikes are slightly deformed, but oriented in a NE-SW orientation. The localized nature of shearing in a variety of mediums paired with systematic orientation of shear zones with antithetic kinematics indicates that strain was predominately coaxial internal to the Mm (Cavalcante and Fossen, 2017; Regan et al., in review).

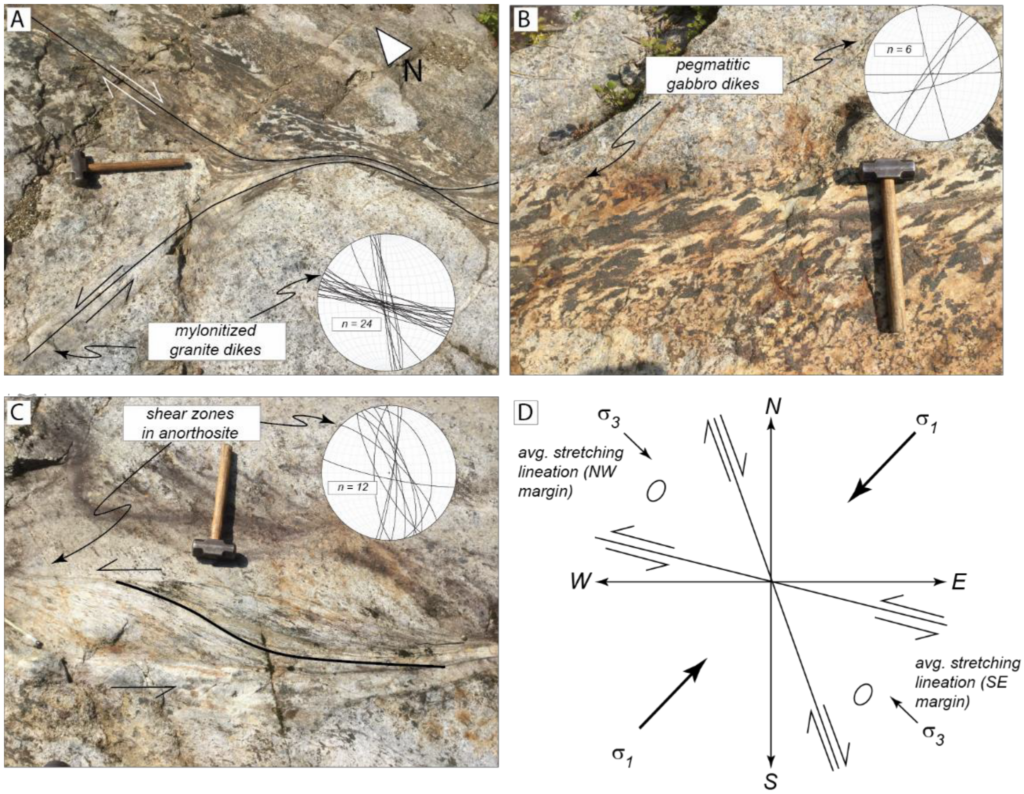


Figure 2: Representative photographs of the Bennies Brook landslide (for more information see Chiarenzelli et al. 2015). A) Mutually off-setting shear zones with antithetic kinematics suggesting a conjugate origin; B) Internaly strained pegmatitic gabbro dike with dextral shear sense; C) localized sinistral shear zone in anorthosite; D) schematic diagram of conjugate relationships from Bennies Brook slide with stretching lineation averages from margin rocks discussed herein labeled.

Deformation along the margin of the Marcy massif

As noted in Balk (1931) and Buddington, (1939), fabric trajectories parallel the contact of the Mm with surrounding country rock. 1:24,000 scale mapping along the southeastern margin of the Mm, focused on the structural setting and distribution of IOA-deposits hosted by the Lyon Mountain granite (Chiarenzelli et al., 2017), has produced new structural constraints on fabrics parallel to the margin of the Mm. At its southeastern margin, the Mm is rimmed by a variably thick zone of fine-grained (Whiteface- facies) gabbroic anorthosite (0.25 - > 1.0 km; Kemp, 1898), that generally displays a strong foliation and mineral stretching lineation. Isolated regions internal to the Mm have km-scale patches of deformed gabbroic anorthosite, interpreted as extensional klippe of the marginal package of rocks. These marginal rocks referring to the package of strongly deformed rocks rimming the anorthosite (anorthosite and country rock) contain granulite progressing to amphibolite facies metamorphic assemblages, and dip moderately to the southeast, away from the Mm. The boundary of the anorthosite, and host tectonites, are folded by open, upright folds shallowly plunging to the east-southeast. This generation of folds (F_3 of Regan et al. (2015)) is associated with plutons of the Lyon Mountain granite and may have facilitated its emplacement (Chiarenzelli et al., 2017).

Structural analysis of marginal rocks provides new insight into the geometry and kinematics of the Mm (Fig. 3). Stereonet analysis of foliation measurements form a girdle with a principal β-axis of 26° to 146° (n = 479). Stretching lineation measurements girdle about the mean foliation (045°, 25°; n = 111) with a mean orientation parallel with the calculated β-axis derived from foliation measurements (Fig. 3b). Consistent kinematic indicators

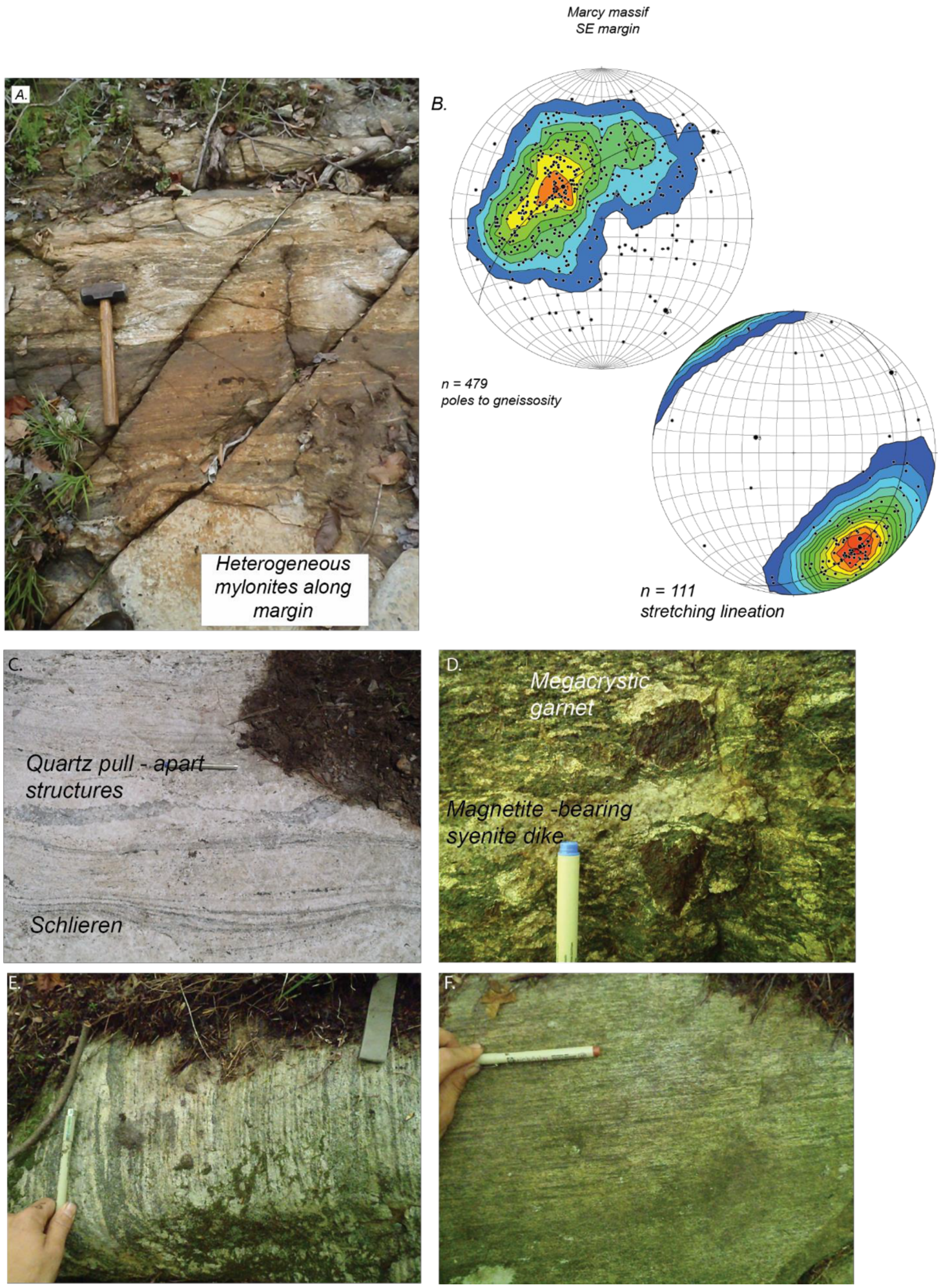


Figure 3: Representative field photographs and structural summary of marginal rocks along the SE margin of the Mm. A) Heterogeneous mylonites in the Whiteface-facies anorthosite; B) lower hemisphere projections of structural elements, upper left: poles planes of foliations, lower right: stretching lineation measurements; C) well-layered Lyon Mountain granite with quartz pull-apart structures and schlieren; D) syenite dike cross-cutting ferrodiorite within the marginal package of rocks with megacrystic gore-mtn type garnet present adjacent to the contact (for more information see McLelland and Selleck, 2011); E) strongly deformed gabbroic anorthosite; D) mylonitized gabbroic rock in marginal shear zone

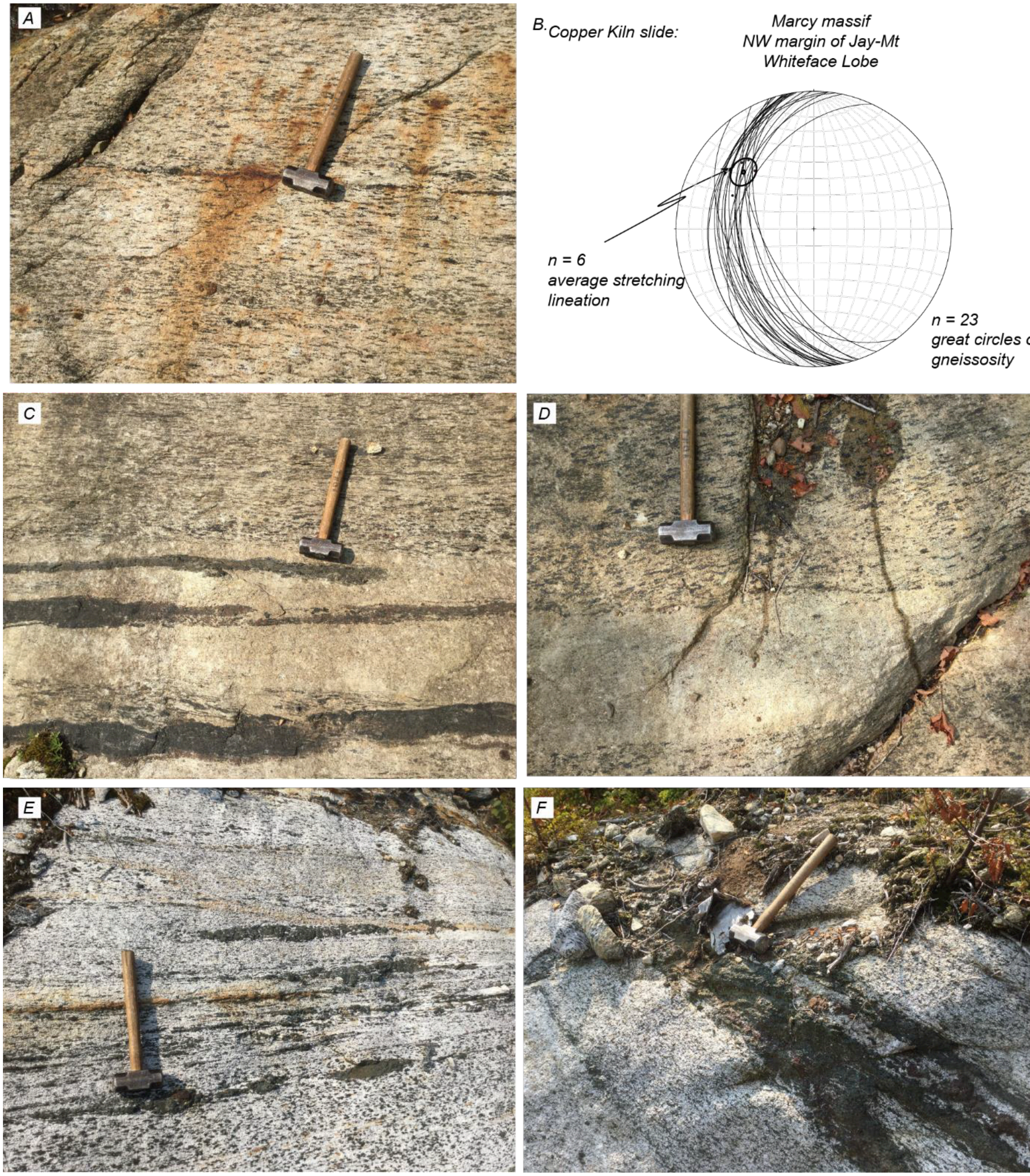


Figure 4: Representative field photographs and structural summary of the Copper-Kiln landslide. A) Strongly deformed gabbroic anorthosite with garnet porphyroblasts; B) lower hemisphere projection of foliation measurements (great circles) and stretching lineations; C) leucogranitoid sheet with preserved and relatively undisturbed mafic layers; D) leucogranitoid sheet with obliquity between host rock gneissosity and intrusive contact; E) strongly deformed gabbroic anorthosite with abundant dismembered calc-silicate xenoliths; F) Strongly deformed skarn rock xenoliths in protomylonitic gabbroic anorthosite

suggest oblique-normal shear sense of top-down to the southeast. Syn- to post-kinematic metamorphic assemblages consisting of hornblende ± garnet ± clinopyroxene ± orthopyroxene are interpreted to record peak- to post peak-metamorphic conditions. Evidence of post-kinematic metamorphism is generally preserved as coronae, and within marginal rocks, garnet envelopes lineated orthopyroxene and hornblende. These data suggest that deformation occurred during peak Ottawan metamorphic conditions within the Adirondack highlands (Spear and Markussen, 1997), and that the anorthosite behaved as a rigid body during granulite-facies deformation and subsequent leucogranite plutonism synchronous with regional cooling and decompression (Spear and Markussen, 1997; Chiarenzelli et al., 2017; Regan et al., in review). In-situ U-Th-total Pb geochronology of syn-kinematic monazite corroborates these interpretations, constraining the timing of deformation within the Mm detachment zone from 1070-1060 Ma (Regan et al., in review).

The Copper-Kiln landslide is located north of Wilmington, NY, within 2 km of the northwestern margin of the Jay-Mt. Whiteface lobe within the Mm (Fig 1c). It exposes over 0.5 km of continuous bedrock exposure. The landslide exposes deformed heterogeneous gabbroic anorthosite of the Whiteface facies (Fig. 4a). With increasing elevation there are abundant screens of dismembered and strongly deformed calc-silicate xenoliths of varying composition including skarns with wollastonite, garnet, and diopside. All rocks exposed along the landslide have a nearly constant foliation of 172°, 42° (RH rule; Fig. 4b), and a variably developed mineral stretching lineation plunging 34° to 309°. Kinematics are difficult to identify on the landslide and give varying senses, but overall a reverse/sinistral sense of shear is interpreted based on exposures closer to the actual margin of the Mm. There are abundant, but cryptic, leucogranite and syenite sills preserving subtle obliquity with host rock gneissosity (Fig. 4c,d). They are similar in color and texture on the weathered surface, making them difficult to see. Locally, these late intrusive rocks fill in boudined gabbro layers within the gabbroic anorthosite, suggesting emplacement during deformation; however the relatively fine grain sizes and internally undeformed state suggests a late syn- to post-kinematic relationship (McLelland et al., 2001).

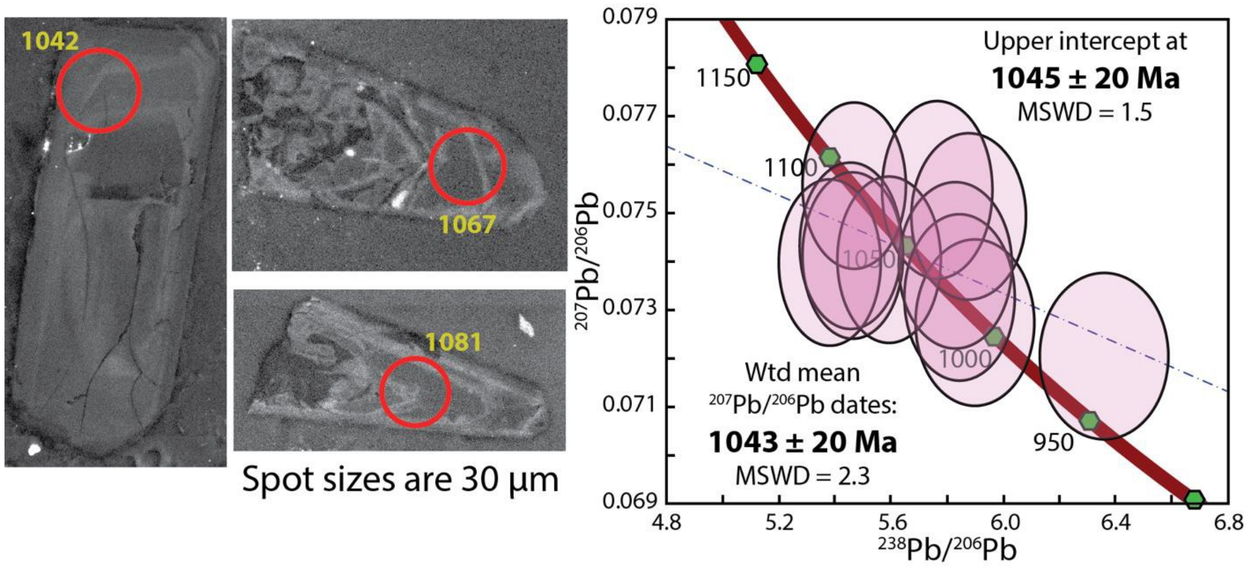
ANALYTICAL DATA

Geochronology

Sample CKS-1 is a syenitic sill that is subconcordant to the dominant foliation in the northeastern lobe of the Marcy massif. Several of these intrusions are exposed in the Copper Kiln slide. We dated zircon in this sill via laser ablation inductively coupled mass spectrometry (LA-ICPMS) in order to: 1) determine the timing of leucogranitoid intrusion into the Marcy massif, and 2) place a minimum constraint on the timing of fabric development in this part of the Marcy massif. Mineral separation and mounting were performed at the University of Arizona and cathodoluminescence (CL) imaging was done at Middlebury College. Isotopic and trace element analyses of zircon were performed at the University of Massachussetts – Lowell on an Agilent 7900 quadrupole ICP-MS with a Teledyne CETAC LSX-213 laser ablation system using a 30 μm spot size.

Zircon grains from this sample take the form of either: 1) euhedral, oscillatory-zoned grains, or 2) xenocrystic (~1150 Ma) cores surrounded by euhedral, pointy overgrowths with oscillatory zoning (Fig. 5). We interpret the overgrowths to have grown directly from a melt during emplacement and crystallization of the syenite sill. Out of 40 analyses, 15 analyses from both oscillatory zoned grains and euhedral pointy overgrowths were "concordant" (e.g. overlapping within 2σ uncertainty). Some of these analyses gave spuriously high Ti and LREE concentrations, which we interpreted to be contaminated by inclusions. The 11 concordant analyses of inclusion-free zircon (based on trace element concentrations) give a weighted mean ^{207}Pb/^{206}Pb age of 1043 ± 20 Ma (MSWD = 2.3), and a Concordia upper intercept age of 1045 ± 20 Ma (MSWD = 1.5; Fig. 5). These dates are consistent with the syenite sills intruding the Marcy anorthosite during orogenic collapse and widespread intrusion and crystallization of the Lyon Mountain granite at c. 1050 Ma (e.g. Chiarenzelli et al., 2017), and place a minimum age constraint on deformation in the northeastern part of the Marcy massif.

We used the Ti in zircon thermometer (Watson et al., 2006) to place constraints on crystallization temperature of the sill. Ti concentrations range from 5.5 to 15.6, giving a range of Ti in zircon temperatures (assuming a_{TiO2} = 0.8, and a_{SiO2} = 1) of 712 ± 3 to 813 ± 13 °C, with a weighted average of 726 ± 13 °C. We note here that our values for a_{TiO2} and a_{SiO2} to calculate temperature are conservative maxima, as the timing of zircon crystallization relative to quartz and Ti-bearing phases from the melt is unknown. The zircon crystallization temperatures derived here are thus minima, as decreased a_{TiO2} or a_{SiO2} would serve to increase apparent temperature. These temperatures are similar to those estimated from granulite facies metamorphic assemblages within the Marcy Massif (e.g. Spear and Markussen, 1997) that developed at c. 1040-1050 Ma (Peck et al., in press). The lack of obvious chilled margins in the sill and minimally retrogressed granulite-facies assemblages in the adjacent gabbroic metaanorthosite suggest intrusion into hot (> 700 □C) subsolidus crust of the Marcy Massif at 1045 ± 20 Ma.



. Figure 5: Geochronology summary for U-Pb zircon data discussed in text. Sample of leucogranitoid sheet

INTERPRETATIONS

The Mm is rimmed by a thick zone of high grade tectonites that preserve evidence of progressive strain parallel to, and around, the rigid anorthosite body at ca. 1060-1040 Ma. Lower hemisphere

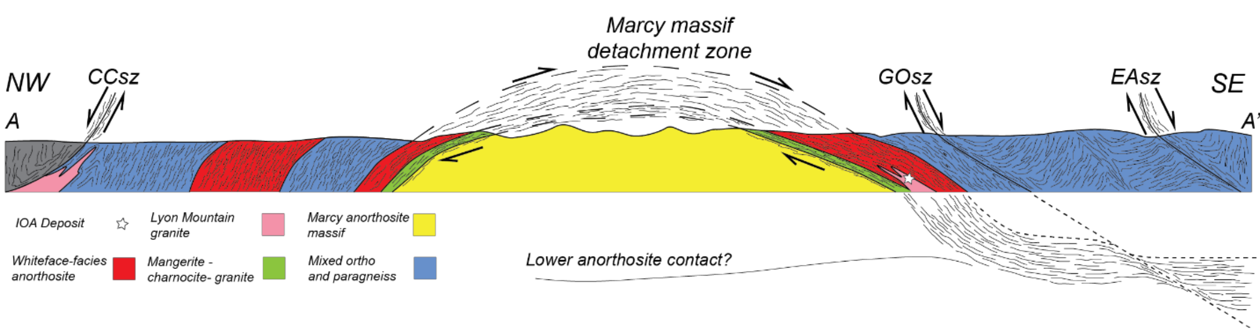


Figure 6: Schematic cross section labeled on Fig. 1b of the Adirondack Mountains with new structural and kinematic data taken into account. The Mm is draped by a southeast-directed, domed, detachment which likely formed during initial extension of the Adirondack highlands during peak metamorphic conditions within the Mm.

projections of the localized conjugate shear systems internal to the Mm suggest a least compressive stress orientation of NW-SE, which is where stretching lineations defined by granulite-facies mineral assemblages from the southern and northern margin plot. We interpret this to suggest that deformation of the margins of the Mm occurred at granulite-facies conditions. Evidence that strain was coaxial within the core of the Mm and subsimple along the margin suggests that the Mm partitioned (sub)simple components of shear along the margin. Therefore, strain was not only localized along the margin, but also partitioned around the 3000 km^2 Mm. Kinematic indicators from the southeastern margin of the Mm suggest top-down and to the southeast relative motion, whereas along the northern margin of the Mm, shear-sense indicators indicate top-up to the southeast relative motion. Fig. 6 shows a schematic cross section of the Adirondack Mountains with the new structural information taken into account, and shows that the Mm is draped by a domed, SE-directed detachment, referred to here as the Marcy massif detachment zone.

The Mm detachment zone shares many of the geometric features of other well documented extensional gneiss domes and metamorphic core complexes from the Grenville Province (Busch et al., 1999; Rivers and Schwertdner, 2015; Dufrechou, 2017). However, the core is predominately composed of undeformed, but metamorphosed anorthosite, and hence is referred to as a metaigneous dome. Similarly, the Morin anorthosite is draped by a domed extensional shear zone (Soucy La Rouche et al.,, 2015; Defrechou, 2017). Monazite and zircon geochronology firmly establish the timing of deformation within the Mm detachment zone to 1070-1060 Ma, with local evidence for even younger deformation (Peck et al., in press). This immediately pre-dates more localized and bivergent extensional structures to the NW and SE of the Mm, like the Carthage-Colton shear zone (Selleck et al., 2005), the East Adirondack shear zone (Wong et al., 2011), and the Grizzle Ocean shear zone (Regan et al., in review). We interpret the Mm detachment zone to have initially formed at granulite-facies metamorphic conditions and at the onset of structural collapse of the southern Grenville orogeny.

The Lyon Mountain granite is an extensive leucogranitic suite that rims the Mm, and hosts abundant Fe-oxide – apatite deposits of current economic interest (Long et al., 2010; Valley et al., 2010; 2011; Chiarenzelli et al., 2017). Emplacement of the Lyon Mountain granite coincides with extensional collapse along the Carthage-Colton shear zone and East Adirondack shear zone (Selleck et al., 2005; Wong et al., 2011). Near the margin of the southeastern Mm, the Lyon Mountain granite forms numerous plutonic bodies that are associated with late and open folds, which likely accommodated protracted emplacement (Chiarenzelli et al., 2017), including hinges of the detachment zone fabric. Notably, the IOA deposits hosted by the LMG appear to correspond to relict hinge regions within the pluton, and are generally within several km of the Mm itself. Leucogranite and syenite sills within the gabbroic anorthosite exposed along the Copper-Kiln landslide are interpreted as relatively early Lyon Mountain granite intrusions that utilized the detachment fabric to ascend, and may mark the last gasp of motion along the detachment. Therefore, the Mm detachment zone initiated at granulite-facies pressure- temperature conditions, and as doming occurred, strain was localized into bivergent shear zones on both sides of the Mm detachment zone. During continued collapse, folding of the Mm detachment zone facilitated the emplacement of the Lyon Mountain leucogranite (Chiarenzelli et al., 2017).

Evidence for fluid flow within the Mm detachment zone is preserved in multiple rock types and mineral assemblages. IOA deposits hosted by the Lyon Mountain granite are associated with extensive sodic alteration, which is generally within several km of the margin of the Mm. Gore Mountain megacrystic garnet, the New York state mineral, has been interpreted as the result of metasomatic reactions catalyzed by leucogranite and pegmatite intrusions within AMCG lithologies, most of which are in relatively close proximity to the Mm. Lastly, Valley and O'Neil (1982) recognized low δO^{18} values in calc-silicate lithologies adjacent and enclosed within anorthosite, interpreted to require a shallow emplacement. Subsequent work by Clechenko et al. (2003) demonstrated that zoned garnet within these lithologies also contain a low δO^{18} signal interpreted to require surficial water interaction during Mm crystallization and emplacement. However, given the abundant independent lines of evidence for fluid flow within the detachment, it seems possible that the apparent interaction with meteoric water may instead have occurred during Ottawan collapse. These observations suggest that the Mm detachment zone facilitated magmatic and fluid flow from various sources ranging from magmatic to potentially surficial, and thus may have provided an ideal location for classic Adirondack ore deposits to have formed.

CONCLUSIONS

The Mm detachment zone is a thick shear zone that envelopes the Marcy anorthosite massif in the Adirondack Highlands. It was active during peak metamorphic conditions within the Adirondack highlands, and specifically within the Mm. The shear zone formed during onset of extensional collapse of the southern Grenville Province during final assembly of Rodinia at ca. 1070 Ma. Recognition of domed extensional structure surrounding the Mm helps explain numerous outstanding questions in Adirondack geology, including the distribution of major ore deposits, the geometry of late syn-extensional leucogranitic bodies, existing thermobarometric work, and geochronology. We welcome lively discussion on the outcrop and hope everyone enjoys the rocks

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ROAD LOG

Carpooling is required! Parking at the trailhead is extremely limited. To consolidate vehicles, meet in the parking lot at Wilmington Town Beach at Lake Everest, Wilmington, NY at 9:00 am. If possible, please carpool from the Lake George area with others who are staying there for the weekend. From the Wilmington Town Beach, we will carpool to the trailhead, which is located c. 5.9 km to the northwest, at the intersection of Bonnieview and John Bliss Road.

0.0 – 0.1: Depart Wilmington town beach on Bowman Lane, take right on Bonnieview Rd

0.1 – 3.4: Arrive at Copper-Kiln (or Cooper – Kill) trailhead, parking on west side of Rd (left side if headed north). Some parking on shoulder .

Hike for approximately two miles on the trail (gradual up hill) until a sharp left hand turn is reached with piled up down trees. We will stop and drink some water and introduce the region here. Follow the trip leader to the landslide (down hill to the north). There will be some scrambling to get to the first outcrop over the outwash.

Stop 1: Deformed gabbro and gabbroic anorthosite

(UTM: 0592904 4920688)

The first stop is not connected by continuous exposure to the rest of the slide. It is located in the outwash of the landslide. The pavement outcrop exposes deformed gabbroic anorthosite and gabbroic gneiss. There is very minor obliquity between the contact between the two lithologies and penetrative gneissosity indicating that a higher angle relationship may have been progressively rotated into parallelism. There is abundant syn-kinematic hornblende +/- biotite at this outcrop consistent with decompression from peak granulite-facies metamorphism during shear.

Figure 7: Stop 2 view down the landslide from the beginning of continuous exposure

Stop 2: Bottom of the Copper-Kiln landslide

(UTM: 0592531 4920764)

The base of the landslide composed of gabbroic anorthosite to fine-grained anorthosite with diffuse contacts. Coarse orthopyroxene porphryoclasts are aligned in the predominant foliation and rimmed by hornblende. Several garnet porphyroblasts are present, but almost entirely replaced with randomly oriented hornblende. The predominant foliation dips moderately to the west northwest. There are also two Neoproterozoic mafic dikes approximately 10 cm wide.

Stop 3: Subconcordant leucogranite to syenite intrusions in anorthosite
(UTM: 0592455 4920760)

Figure 8: Concordant leucogranitoid sheet in strongly deformed gabbroic anorthosite

Along the landslide there are abundant meter-scale subconcordant syenite to leucogranitic sills, preserving varying degrees of obiquity with host rock gneissosity. They are difficult to spot at first as they weather to a pale gray/pink and are initially difficult to distinguish from recrystallized anorthosite. The dikes contain minimal evidence for high degrees of strain, but the extent of post kinematic annealing still remains problematic. However, the preservation of perthitic textures, and subhedral and isolated mafic minerals, we interpret minimal subsolidus strain to have occurred subsequent to intrusion. They lack the very recognizeable mesoscopic fabrics contained in surrounding anorthosite to gabbroic anorthosite gneisses. This dike was analyzed for U-Pb zircon geochronology and Ti in zircon thermometry. Based on results discussed above, we interpret the leucogranitoids to be members of the Lyon Mountain ferroan leucogranite suite (Chiarenzelli et al., 2017), and to have been emplaced synchronous with extensional collapse of the Adirondack Highlands (Regan et al., in review). The Mm detachment zone may have aided in their initial emplacement as seen here.

As we continue walking up the slide, there will be countless opportunities to discuss the relationships of the leucogranitoid sheets and host rocks. A Google Earth file of all data available on NYSGA website with all measurements, locations, photographs, and descriptions.

Stop 4: Skarn near top of landslide
(UTM: 0592202 4920693)

As the landslide steepens and we approach the headwall, you will notice an increase in the number of pods, screens, and partially digested and subsequently deformed calc-silicate xenoliths. Xenoliths range in scale from cm-scale to several meters in thickness and display a varied mineralogy of garnet, diopside, wollastonite, dolomite, titanite, among others. Titanite can be seen in hand sample and is the root beer colored mineral in the calc-silicate lithologies. Thick quartz-veins several cm in thickness are also common in this package of rocks.

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