GEOLOGIC SETTING AND CHARACTERISTICS OF ADIRONDACK ANORTHOSITE AND RELATED MANGERITE-CHARNOCKITE-GRANITE (AMCG SUITE)

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The Adirondack Mountains represent a southwestern extension of the Grenville Province via the Thousand Islands – Frontenac Arch region of the St. Lawrence River (Fig. 1). The region is topographically divided into the Adirondack Highlands and Lowlands separated by the Carthage-Colton Mylonite Zone (CCMZ, Fig. 2). The former is underlain largely by orthogneisses metamorphosed to granulite facies and the latter by upper-amphibolite grade metasediments, notably marbles. Both sectors have experienced multiple deformations resulting in refolded major isoclines. Due to the complexity of the terrain, it was difficult to establish a reliable geologic history prior to the advent of U-Pb zircon geochronology. Silver (1969) pioneered a landmark study based on multigrain thermal ionization mass spectrometry (TIMS). His investigations indicated high-grade metamorphism at ca 1050 Ma and widespread intrusion of granitoids at ca 1120 Ma. These early analyses required very large zircon fractions (hundreds of mg.) and did not have the advantages of hand picking or air abrasion; hence, they represent mixed ages and serve only as rough guidelines. In the 1980's McLelland and Chiarenzelli initiated an investigation in which 30 representative samples were dated by multigrain, air-abraded TIMS methods (McLelland et al 1982, McLelland and Chiarenzelli, 1990). Subsequently, these results have been extended by single grain TIMS and SHRIMP techniques and most of these are summarized in McLelland et al. (1996), McLelland et al. (2001), Wasteneys et al (1999), and McLelland (2004) from which the first portion of this article has been derived. The picture that has emerged is one of a tripartite division of Adirondack geologic history, as summarized below.

The earliest recognized rocks in the Adirondacks consist of calcalkaline tonalites and granodiorites dated at ca 1350 – 1250 Ma and exposed in the southern and eastern Adirondack Highlands (McLelland and Chiarenzelli, 1990). Rocks of similar composition and age have been recognized in the Green Mountains of Vermont (Ratcliffe et al, 1996) and the Proterozoic of western Connecticut (Walsh and Aleinikoff, 2002). In addition, calcalkaline plutonic rocks ranging in age from 1270-1220 Ma are common within the western Central Metasedimentaery Belt (CMB) of the Canadian Grenville Province (Fig. 1). All of these calcalkaline orthogneisses have been interpreted as arc-related additions of juvenile crust to this sector of the Province during the interval ca 1400-1220 Ma (Fig. 3). Moore and Thompson (1980) proposed that this interval was characterized by repeated arc accretion to the southeast margin of Laurentia and referred to this protracted sequence of events as the Elzevirian Orogeny. Because Elzevirian plutons are overprinted by ca 1100-1000 Ma high-grade metamorphism, Moore and Thompson (1980) introduced the term Grenville Orogenic Cycle consisting of an early Elzevirian Orogeny and a younger (ca 1100-1000 Ma) Ottawan Orogeny that, together, replaced the old Grenville Orogeny and emphasized the existence of two major pulses of orogeny separated by an extensional interval of sedimentation represented by the Flinton Group in the CMB. In the Adirondacks, Elzevirian accretion appears to have extended to ca 1200-1160 Ma when the Adirondack Highland-Green Mountain Terrane collided with leading edge of the Frontenac Terrane of the CMB, which was at that time represented by the Adirondack Lowlands (Wasteneys et al 1999). This culminating accretionary event resulted in widespread magmatic and tectonothermal events that are referred to in adjacent Canada as the Shawinigan Orogeny (Corrigan and van Breemen, 1997, Rivers, 1987), and this terminology is adopted here.

Subsequent to the Shawinigan Orogeny, there does not appear to have been any significant regional deformation in the Adirondacks until ca 1090 Ma when, following a brief interval (ca 1103-1090 Ma) of granitic magmatism (Hawkeye suite, McLelland et al, 1996), the entire Grenville Province began to feel the effects of the Ottawan Orogeny that is thought to have been the result of collision with a continental-scale craton (Amazonia?) with the suture zone somewhere to the southeast of the present day Appalachians (Fig. 3). Geothermometry, geobarometry, and seismic investigations document that during the Ottawan Orogeny the Adirondack Highlands region obtained double crustal thickness and underwent granulite facies metamorphism and nappe emplacement (Bohlen et al, 1985, Valley et al, 1990, McLelland et al., 1996). The major contractional phase of the Ottawan Orogeny appears to have been over by ca 1050-1040 Ma, since minimally deformed subunits of the Lyon Mountain Granite were intruded at this time, especially the undeformed fayalite granites at Wanakena and Ausable Forks (McLelland et al, 2001). Locally, younger events of lesser magnitude continued to affect the region until ca 990 Ma and are recorded by metamorphic zircon and monazite.

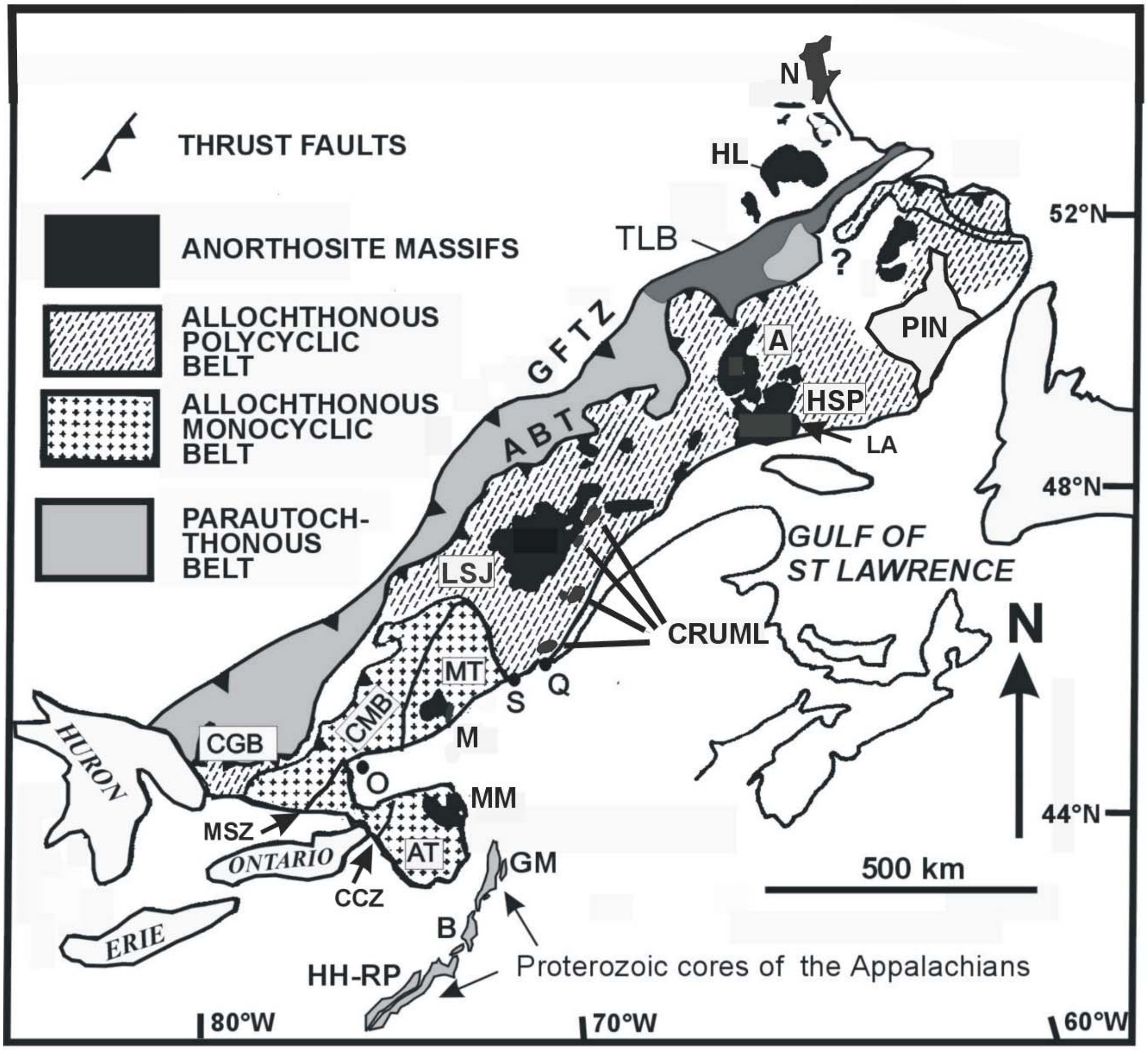


Fig. 1. Generalized location map of the Adirondacks as a southwestern extension of the Canadian Grenville Province whose three major tectonic divisions (Rivers, 1997) are shown. ABT-Allochthonous Boundary Thrust; GFTZ- Grenville Front Tectonic Zone; TLB (dark gray) - Trans-Labrador Batholith, GM – Green Mountains, H – Housatonic Mountains, HH-RP – Hudson Highlands and Reading Prong. The major anorthosite massifs (with ages) of the region are: MM- Marcy (ca 1150 Ma), M) Morin (ca 1160 Ma), LSJ) Lac St. Jean (ca 1150 Ma), HSP) Havre St-Pierre, A) Atikonak (ca 1130 Ma), ME), HL) Harp Lake (ca 1450 Ma), N) Nain-Kiglapait (ca 1300 Ma),; P) Pentecote (ca 1350 Ma). Age references: 1- 2, Hamilton et al. (2002), 3-7, Emslie and Hunt (1989), 4) Higgins and van Breemen (1996), 5) van Breemen and Higgins, (1993) Hamilton et al (1998), 9) Machado and Martignole (1988).

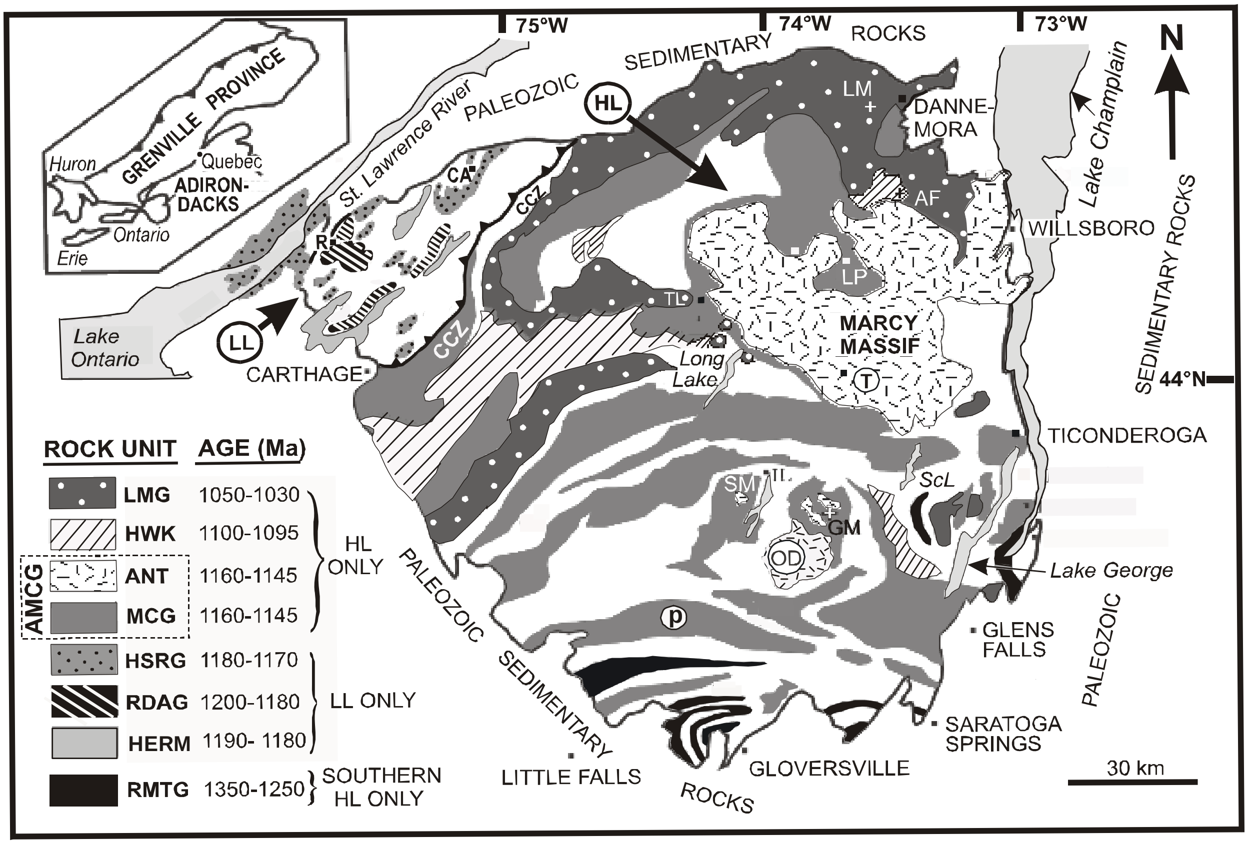


Fig. 2. Generalized geological/geochronological map of the Adirondacks. Units designated by patterns and initials consist of igneous rocks dated by U-Pb zircon geochronology with ages indicated. Units present only in the Highlands (HL) are: RMTG – Royal Mountain tonalite and granodiorite (southern HL only), HWK - Hawkeye granite, LMG – Lyon Mountain Granite and ANT - anorthosite. Units present in the Lowlands (LL) only are: HSRG – Hyde School and Rockport granites (Hyde School also contains tonalite), RANT – Rossie diorite and Antwerp granodiorite. Granitoid members of the AMCG suite (MCG) are present in both the Highlands and Lowlands. Unpatterned areas consist of metasediments, glacial cover, or undivided units. CCZ- Carthage-Colton Mylonite Zone, MM- Marcy anorthosite massif, OD Oregon Dome, SM – Snowy Mountain, LM – Lyon Mountain, IL – Indian Lake, SL – Saranac Lake, GO – Gouvernour, R – Rossie, CA – Canton. Locations for samples discussed in text: a)-Rooster Hill megacrystic charnockite, b)-Piseco leucogranitic ribbon gneiss, c)- Oregon Dome ferrodiorite, d)- Gore Mt. mangerite, e)-Snowy Mt mangerite, f) Schroon Lake granitic gneiss, g) -Minerva mangerite, h) North Hudson metagabbro, i) Woolen Mill gabbro and anorthosite, j)- anorthositic pegmatite and clinopyroxene-plagioclase dike in Ausable River at Jay, L) Yard Hill jotunite, m)- Bloomingdale mangerite, n) mangeritic dike cross-cutting anorthosite northeast of Tupper Lake Village, o)– mangerite southeast of Tupper Lake Village, p)- Rapakivi granite in Stark anticline, q) - Oswegatchie leucogranite r-Diana pyroxene syenite, s-Croghan granitic gneiss, t) Carthage anorthosite.

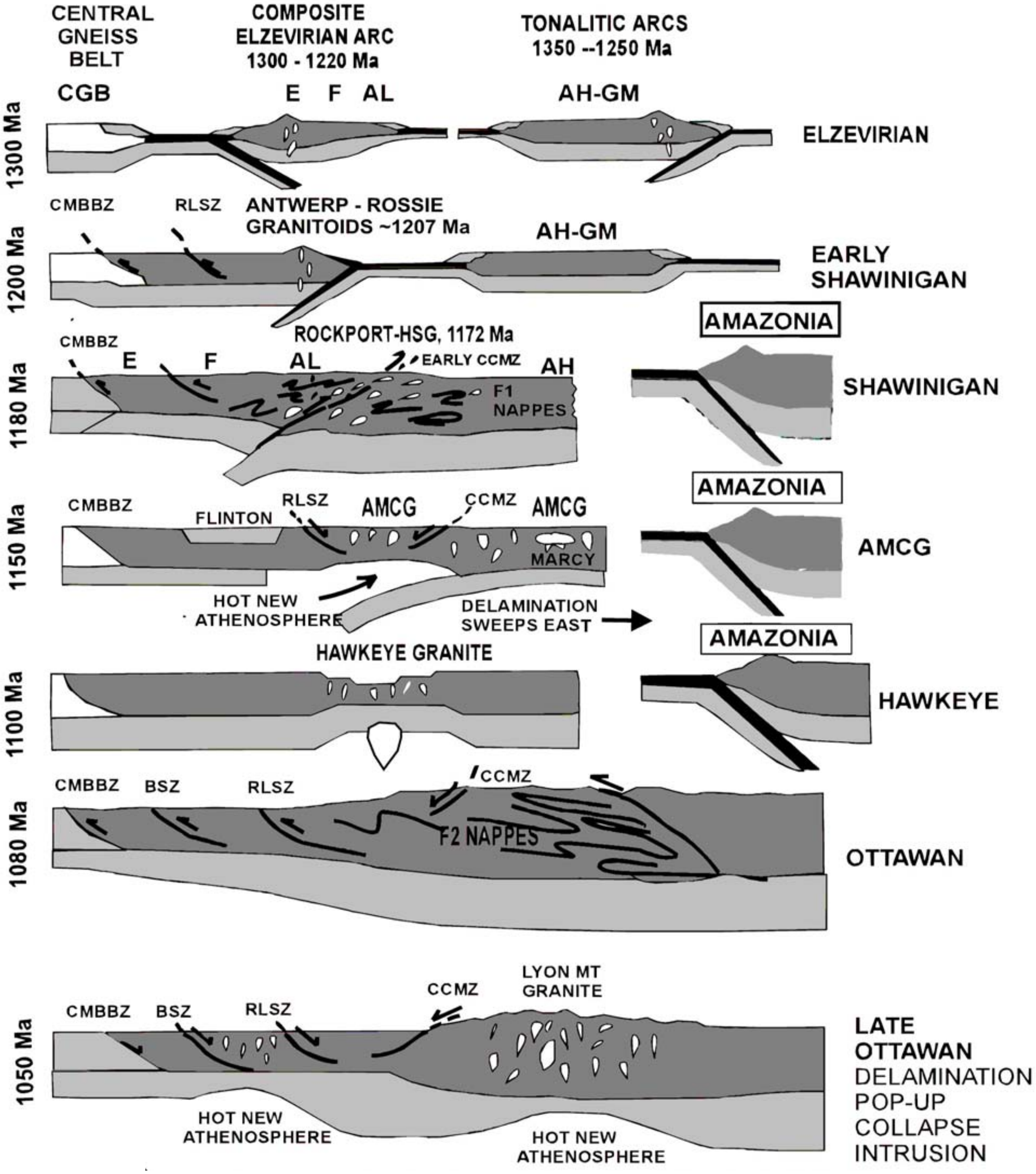


Fig. 3 Plate tectonic synthesis of the Adirondack region

For decades controversy has existed over how and when the Adirondack anorthosite massifs and associated granitoids are related to one another. Buddington (1939, 1969), Davis (1969), and Postel (1952) regarded the anorthosites as early, pre-orogenic intrusions that were slightly older than the AMCG granitoids that crosscut them. In contrast, deWaard and Romey (1969) and Lettney (1969) adopted the model of Martignole and Schrijver (1968) for the Morin anorthosite and proposed that Adirondack anorthosites were synorogenic intrusions and comagmatic with the AMCG granitoids. Silver (1969) emphasized that ca 1050 Ma metamorphic zircons in the

Marcy massif indicated that the anorthosite was older than this event and also predated the ca 1120 Ma AMCG granitoids that crosscut it. The U-Pb zircon results of McLelland and Chiarenzelli (1990a,b) confirmed Silver's interpretation by establishing the ca 1090-1050 Ma Ottawan Orogeny in the Adirondacks (See also Mezger et al, 1991) and documenting that the AMCG granitoids were emplaced at ca 1145 ± 15 Ma thus fixing a minimum age for the anorthosites that they crosscut. This placed AMCG magmatism subsequent to the Shawinigan Orogeny and ~50 Ma prior to the Ottawan Orogeny and was consistent with the ages of the large anorthosite massifs in the Canadian Grenville (Emslie and Hunt, 1992).

The eastern Grenville Province contains a number of mid-Proterozoic AMCG complexes cored by large anorthosite massifs (Fig. 1) accounting for ~20% of the region's area (McLelland, 1989). Within the Adirondacks, the Marcy anorthosite massif (Figs. 1,2) has long been regarded as typical of mid-Proterozoic massifs worldwide (Ashwal 1993). The smaller Oregon Dome and Snowy Mt bodies (Fig. 2) are compositionally and mineralogically similar to the Marcy massif. Several other small occurrences exist on a scale too small to be shown on figure 2. Adirondack anorthosites are of the andesine-labradorite (An_{45}-An_{55}) variety and contain magnetite and ilmenite reflecting a relatively low fO_2 (Anderson 1987) and resembling other large massifs in the Grenville Province. In addition to these low fO_2 massifs, several smaller and distinctive alkalic and hemoilmenite-bearing andesine ($An_{30}Or_{11}$-$An_{40}Or_7$) anorthosites occur in Quebec (Owens and Dymek, 1999) and are also present in the Proterozoic core of the southern Appalachians (Owens and Samson, 2001). These late- to post-tectonic bodies are clearly more oxidized and younger (ca 1050-1010 Ma) than the larger, more reduced massifs, such as the Marcy, that form the subject of this paper.

The Marcy massif is roughly elliptical (Fig. 2) with its long dimension (NW-SE) extending ~100 km and its short (NE-SW) dimension measuring ~60 km. Gravity models suggest a slab-like shape some 3-5 km thick with two funnel-shaped feeder pipes extending to ~10 km. Like other igneous bodies of this size, the Marcy massif is a composite intrusion consisting of a variety of anorthositic and leucogabbroic members that were repeatedly emplaced in an unspecified number of pulses. Following Buddington (1939, 1969), the principle rock types comprising the massif are anorthosite (>90% plagioclase), mafic anorthosite (90- 75% plagioclase), leucogabbro (75 – 65% plagioclase), and gabbro (<65% plagioclase). Together, anorthosite and mafic anorthosite constitute ~90% of the massif. Leucogabbro is concentrated along the borders of the massif where it occurs together with mafic anorthosite to form a deformed, finer-grained, and more mafic border facies surrounding a largely anorthositic core of coarse, little-deformed blue-gray plagioclase. The leucogabbro is commonly referred to as the Whiteface facies (Kemp, 1898), whereas the anorthositic varieties are known as the Marcy facies (Miller, 1919). Modern workers continue to use these designations but with the recognition that two facies are insufficient to describe the complicated nature of the massif and its multiple intrusive pulses. In addition, the margins of the massif commonly contain a complex border facies consisting of rocks that represent commingling of anorthositic and granitoid magmas. Miller (1919) named these hybrid rocks Keene Gneiss for their exposures near the village of Keene. The mixtures can become very complex, because a variety of AMCG magmas, including ferrodiorites, are involved. Within Keene Gneiss, plagioclase xenocrysts incorporated into granitoids or alkali feldspar incorporated into anorthosite, exhibit reaction rims of perthite or plagioclase, respectively (McLelland et al 2002). In addition to the major massif rock types described above, there exists a widespread, small volume (~5%) member of the suite that is best categorized as ferrodiorite or ferrogabbro (McLelland et al. 1994). These very mafic rocks are concentrated near the massif margins where they occur as sheets and dikes crosscutting the anorthosite. They are also present in small volume throughout the massif as thin, wispy and discontinuous veinlets within the anorthosite. McLelland et al (1994) interpreted these titanium-, iron-rich and silica-poor rocks as late differentiates of the anorthosite that were injected by filter pressing. They also proposed that further fractionation of the mafic magma would lead to formation of the ilmenite-magnetite deposits associated with the Marcy massif.

A striking feature of the Marcy facies is the presence within it of rafts of exceptionally coarse anorthosite containing plagioclase crystals with long dimensions of 15-30 cm and up to 45 cm in length. These are found in subophitic intergrowths with both ortho- and clinopyroxene, some of which qualify as "giant pyroxenes" (Fig. X). Emslie (1975) analyzed some of these and found high concentrations of Al_2O_3 (10-15%) indicative of highpressure origins. In almost all occurrences these ultra-coarse assemblages are in the form of rafts surrounded by finer grained varieties of leucogabbro or mafic anorthosite In addition to the exceptionally coarse rafts of anorthosite, there exist large tracts of coarse (4-10 cm) anorthosite consisting of blue gray plagioclase and, 10% mafics. Much of this material exhibits flow alignment of plagioclase laths and must represent mobilized crystal-rich mush. The alignment is interpreted as magmatic rather than tectonic, because neither the plagioclases nor interstitial subophitic pyroxene are deformed. Judging by the high (>90%) concentration of plagioclase laths in these rocks it is probable that they represent cumulates that formed within the post-emplacement massif. The parental magma of these cumulates is thought to be similar in composition to the mafic anorthosite and leucogabbro that enclose the coarse grained rafts and also constitute the Whiteface facies (Buddington, 1939, 1969, McLelland et al, 1994).

DISCUSSION

The results of SHRIMP geochronology of the Adirondack AMCG suite (Fig. 8), together with those of Hamilton et al (1994), are shown graphically in Fig. 7 a, b. These two plots emphasize the narrow range of ages for both the anorthositic rocks and their associated granitoids. This close correspondence is further documented by weighted average age plots for the two groups, i.e., anorthosites, 1155 ± 6 Ma and granitoids, 1158 ± 5 Ma (Fig X2, A, B). Additionally, further refinement of the granitoid data reveals that the four granitic members (Fig YY A) yield a weighted average age of 1148 ± 6 Ma (MSWD = .4, Probability = .93), whereas 7 samples of mangerite and charnockite yield a weighted average age of 1163 ± 7 Ma (MSWD = .2, Probability = .93). The latter age may be especially relevant to models of AMCG genesis, because the less evolved charnockites and mangerites probably represent the earliest members of the group. All of these results are discussed below.

Direct dating of the Adirondack AMCG suite demonstrates that all members are coeval within the interval 1155 ± 10 Ma. This now-established result serves as a powerful constraint on genetic models, both within the Adirondacks and elsewhere in the world. Documentation of the contemparaneity of suite members permits the age of undated anorthosites to be inferred from the ages of associated AMCG granitoids. Thus, for example, the ages of AMCG granitoids dated by Emslie and Hunt (1990) in the Canadian Grenville can now be assigned with confidence to their associated anorthosite massifs, as originally suggested by these authors. Such documentation of absolute age relationships greatly facilitates the crucial goal of constraining and establishing the origin, evolution, and tectonic setting of AMCG complexes. In the following, we utilize the coeval nature of the suite to help construct a self-consistent tectonic-petrologic model of AMCG genesis. Many of the specifics are not new, but their synthesis hinges upon the coeval nature of the suite.

The tectonic setting of AMCG suites has been debated for decades. Emslie (1978), Anderson (1983), and McLelland et al (1996), among others, proposed an “anorogenic” environment for these rocks. It was argued that anorthosites represent derivatives from gabbroic magmas, and the best way to produce these derivatives is to pond gabbroic magma under the density lid at the crust-mantle interface, where they can evolve under quiescent conditions and accumulate plagioclase-rich crystal mushes, fractionate olivine and pyroxene, and decrease their density while they also partially melt the lower crust to produce granitoid magmas (Emslie, 1975, 1978; Ashwal, 1993). In contrast, in an environment of rapid rifting the ponded gabbros would quickly ascend and form basalt flows, new oceanic crust, etc. If, instead, the environment were one of contraction, magmas from diverse sources would become hybridized and/or injected upward prior to fractionation. Accordingly, active tectonic regimes were thought to preclude quiescent environments necessary for fractionation and the accumulation of a plagioclase-rich crystal mush. In contrast, so-called “anorogenic” environments were perceived as capable of providing conditions for quiescent fractionation and genesis of anorthositic magmas and AMCG suites. In the “anorogenic” model, the gabbro’s most likely source would be a mantle plume or hotspot. The “anorogenic” model was also consistent with the observation that, while many AMCG suites occur within tectonic belts, they do not appear to be syntectonic, e.g., Nain Anorthosite Complex.

Although a number of investigators expressed skepticism about “anorogenic” environments (cf., Ashwal, 1993), the most demonstrable flaw in the concept arose from the expansion of U-Pb zircon geochronology in the Grenville Province, including the Adirondacks. By the early 1990’s it became evident that emplacement ages of AMCG granitoids overlapped in time with contractional events taking place within the same general region (Corrigan and Hanmer, 1997, McLelland et al., 1996). Accordingly, the concept of “anorogenic” emplacement was no longer tenable in the region. At the same time, the role of delamination in overthickened, contractional orogens was becoming better understood, especially as it applies to late and post-orogenic magmatism (Sandiford and Turner, 1991). Ultimately, both Hanmer and Corrigan (1997) and McLelland et al (1996) applied the delamination mechanism to the genesis of AMCG suites, especially within the late stages of contractional orogenesis. They argued that once a dense lithospheric keel is delaminated from a thickened orogen, hot replacement athenosphere rises to the crust-mantle interface and produces gabbroic magma. Simultaneously, the orogenic crust, deprived of its high-density root, experiences strong buoyancy forces that result in uplift and the neutralization of horizontal contractional forces that may continue to exist. Orogen collapse along low angle normal faults may take place, but the buoyant, tectonically "neutral", orogen can stay relatively "quiescent" for a substantial period of time. *This set of circumstances results in an orogenic environment that provides all of the stability inherent in supposed "anorogenic" settings but is far superior to the latter, because the concept of a delaminated, buoyant orogen is more consistent with both theory and observables.* An important corollary of the delamination-based model is that it places the genesis of AMCG suites within time intervals that coincide with late- to post-tectonic magmatism, and this is consistent with observations in the Adirondacks and adjacent parts of the Canadian Grenville. Specifically, the voluminous AMCG magmatism dated at ca 1150 Ma (eg, Marcy, Morin, Lac St-Jean, Atikonak massifs, fig 1) immediately follows the Shawinigan Orogeny that affected this portion of the Grenville Province during the interval ca. 1200-1150 Ma (McLelland et al, 1996, Corrigan and Hanmer, 1997, Wasteneys et al, 1999). Similar associations may hold for the ca 1300-1450 Ma Harp Lake, Mistastin, Michikamau and Nain AMCG suites where there now exists compelling evidence that these complexes were associated with funneled, flat-slab subduction in the interval 1460-1230 Ma (Gower and Krogh, 2002). The underiding slab may have involved a spreading center that provided plumbing for ascending mantle melts. Alternatively, instabilities and rollback in the slab may have led to episodes of delamination allowing hot, new athenosphere access to the base of the crust so as to produce AMCG magmatism. On a much smaller scale, the Labrieville, St. Urbain, Roseland, and Montpelier anorthosites fall into the range ca 1050-1000 Ma coeval with late- to post-tectonic events associated with the Ottawan Orogeny (Owens and Dymek,) and its proposed delamination (McLelland et al, 2004).

There currently exist two major petrogenetic models put forward to account for AMCG suite genesis. The first is based upon bimodal magmatism and considers the suite to be coeval but not comagmatic. It has been described in detail by Emslie (1985), Emslie et al, (1994), Ashwal (1993), Weibe (1994), and Fram and Longhi (1992) and represents the most commonly held view of AMCG magmatism. Its principal characteristics are that: a) anorthosites are derived from mantle melts and b) their associated granitoids are the result of melting of the lower crust by heat derived from elevated isotherms and the mantle melts cited in a). The second model utilizes experimental and isotopic evidence to argue for a comagmatic origin for most AMCG suites, and is characterized by a mafic (two pyroxenes and plagioclase) lower crustal (P~ 10-13 kb) source region that melts to produce jotunitic compositions similar to high-aluminum gabbro but containing higher concentrations of Ti, P, and K (Vander Auwera et al, 1998; Longhi et al, 1999). Fractionation of the jotunitic magmas is thought to produce the entire range of AMCG compositions. Both models a) and b) are consistent with a strictly coeval origin for these rocks; however, only the first predicts that granitoids should predate anorthositic members by a narrow time interval. This difference in timing was first noted by Emslie et al (1994) who pointed out that heating of the lower crust by ponded gabbro would lead to early production of granitoid melts leaving behind hot, residual plagioclase-pyroxene restites that could be assimilated by the already fractionating gabbroic magmas. Assimilation-fractional crystallization (AFC) processes would lead to anorthositic magmas characterized by geochemical signatures consistent with lower crustal trace element patterns.

Our strong preference for a coeval but not comagmatic origin for the Adirondack AMCG suite is based in part on observables such as the zones of Keene Gneiss that separate AMCG anorthosite and granitoids and represent disequilibria dominated, physical mixtures between the two magmas. Within these zones, disequilibria is manifested by the reaction rims of perthite around anorthosite andesine and andesine-oligoclase around granitoid perthite (Hamilton et al, 2004). Davis (1968) and Buddington (1968) both drew attention to the absence of correlation between pyroxene (mg#) and plagioclase compositions (An%) within Keene Gneiss, whereas they consistently correlate within the anorthosites and granitoids themselves. These same authors also noted that screens of country rock commonly separate anorthosite from granitoids and imply intrusive relationships. Consistent with this is the observation that ferrodiorites (jotunites) are common in anorthositic rocks but are rare, and of different composition, in associated granitoids. Moreover, the thin veinlets of ferrodioritic material that occur throughout the anorthosites are clearly of local origin and can be seen to occupy small fractures and shear zones just as would be expected from filter pressing. In short, Adirondack ferrodiorite (jotunite) is a late derivative from anorthositic magmas and, contrary to Vander Auwera et al (1998) and Longhi et al, 1999) did not serve as a parental magma for either the anorthosite or the AMCG granitoids. Indeed, the enormous volume of AMCG granitoids in the Adirondacks inveighs against a derivation by fractionation but is wholly consistent with their production as deep crustal melts resulting from mantle-derived heat transported by mantle-derived gabbros whose fractionation at the crust-mantle interface produced ample heat of crystallization resulting in a bimodal suite of granitoid crustal melts and plagioclase crystal mush. Vander Auwera et al (1998) cite de Waard and Romey (1968) in order to claim that “parts” of the Adirondack AMCG suite are examples of fractionation that produces all members of the AMCG as consanguineous derivatives of a single parental magma. The seminal article (de Waard, 1970) setting forth this proposition is based on exposures representing the entire AMCG suite exposed in the bed of Roaring Brook on Giant Mountain in the eastern Marcy massif. McLelland (1992) reinvestigated this locality in great detail and has shown that the relationships present are best accounted for as the result of magma mixing, commingling, and hybridization. Indeed, enclaves originally misinterpreted as xenoliths of Grenville metasediments (Jaffe et al, 1983) in the granitoids can be shown to be the result of commingling between gabbroic and syenitic magmas. At Snowy Mt. (Fig. 2), where deWaard and Romey (1968) collected data that led to their comagmatic proposal, dating reported by Hamilton et al (2004) shows that charnockitic rocks dated at 1174 ± 25 Ma surround a ca 1155 Ma anorthositic core and comagmatism between the two is unlikely. Within the Adirondacks, a supportable case for a comagmatic AMCG suite has yet to be made.

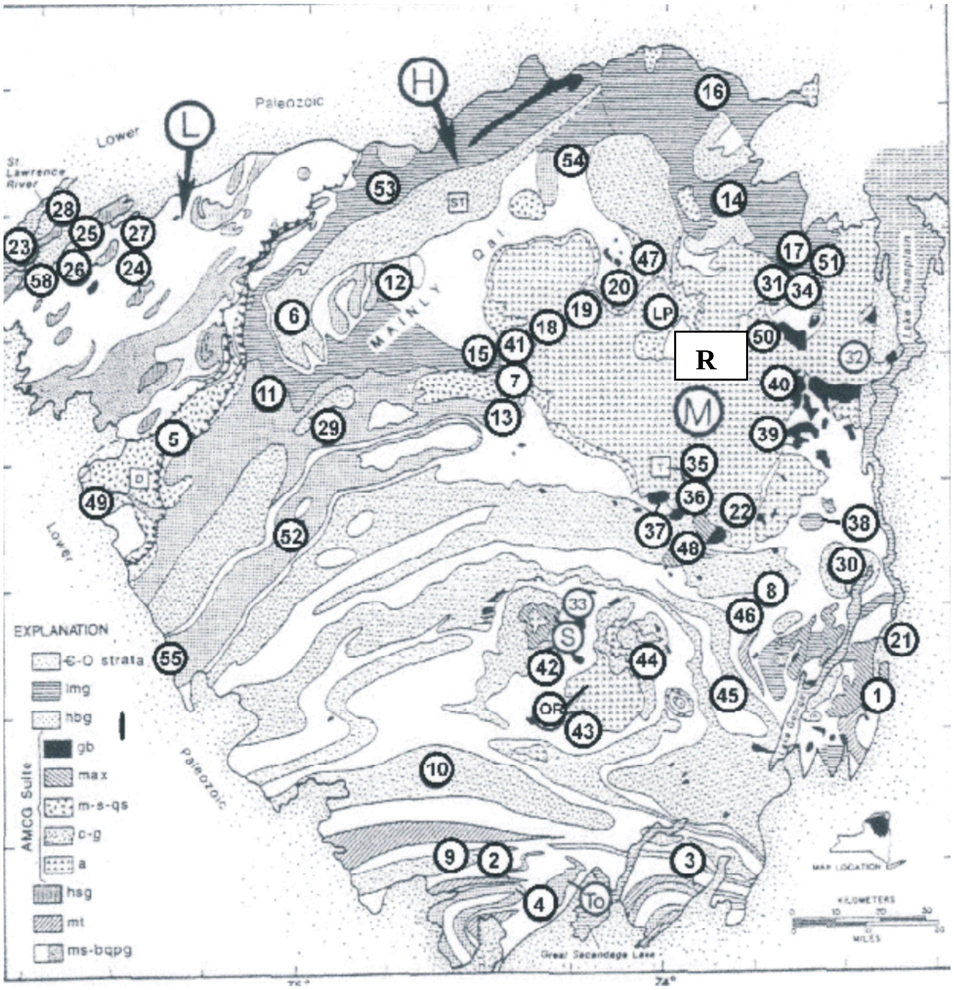


Fig. 4. Locations of samples dated by zircon and listed in Table 1

Table 1

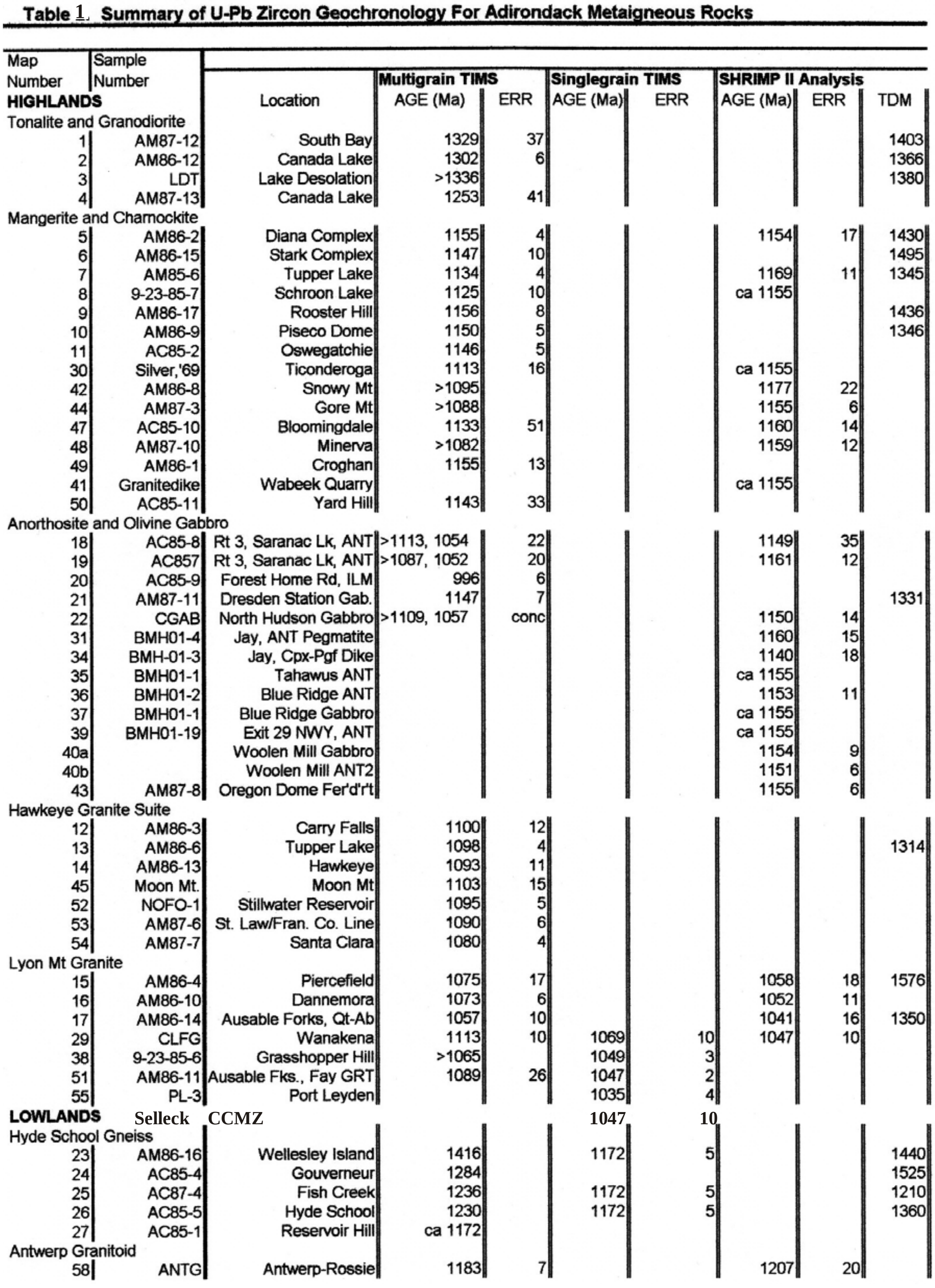


Table 1. Summary of U-Pb Zircon Geochronology For Adirondack Metaigneous Rocks

Map Number	Sample Number	Location	Multigrain TIMS		Singlegrain TIMS		SHRIMP II Analysis		
			AGE (Ma)	ERR	AGE (Ma)	ERR	AGE (Ma)	ERR	TDM
HIGHLANDS									
Tonalite and Granodiorite									
1	AM87-12	South Bay	1329	37					1403
2	AM86-12	Canada Lake	1302	6					1366
3	LDT	Lake Desolation	>1336						1380
4	AM87-13	Canada Lake	1253	41					
Mangerite and Charnockite									
5	AM86-2	Diana Complex	1155	4			1154	17	1430
6	AM86-15	Stark Complex	1147	10					1495
7	AM85-6	Tupper Lake	1134	4			1169	11	1345
8	9-23-85-7	Schroon Lake	1125	10			ca 1155		
9	AM86-17	Rooster Hill	1156	8					1436
10	AM86-9	Piseco Dome	1150	5					1346
11	AC85-2	Oswegatchie	1146	5					
30	Silver,'69	Ticonderoga	1113	16			ca 1155		
42	AM86-8	Snowy Mt	>1095				1177	22	
44	AM87-3	Gore Mt	>1088				1155	6	
47	AC85-10	Bloomingdale	1133	51			1160	14	
48	AM87-10	Minerva	>1082				1159	12	
49	AM86-1	Croghan	1155	13					
41	Granitedike	Wabeek Quarry					ca 1155		
50	AC85-11	Yard Hill	1143	33					
Anorthosite and Olivine Gabbro									
18	AC85-8	Rt 3, Saranac Lk, ANT	>1113, 1054	22			1149	35	
19	AC857	Rt 3, Saranac Lk, ANT	>1087, 1052	20			1161	12	
20	AC85-9	Forest Home Rd, ILM	996	6					
21	AM87-11	Dresden Station Gab.	1147	7					1331
22	CGAB	North Hudson Gabbro	>1109, 1057	conc			1150	14	
31	BMH01-4	Jay, ANT Pegmatite					1160	15	
34	BMH-01-3	Jay, Cpx-Pgf Dike					1140	18	
35	BMH01-1	Tahawus ANT					ca 1155		
36	BMH01-2	Blue Ridge ANT					1153	11	
37	BMH01-1	Blue Ridge Gabbro					ca 1155		
39	BMH01-19	Exit 29 NWY, ANT					ca 1155		
40a		Woolen Mill Gabbro					1154	9	
40b		Woolen Mill ANT2					1151	6	
43	AM87-8	Oregon Dome Fer'd'r't					1155	6	
Hawkeye Granite Suite									
12	AM86-3	Carry Falls	1100	12					
13	AM86-6	Tupper Lake	1098	4					1314
14	AM86-13	Hawkeye	1093	11					
45	Moon Mt.	Moon Mt	1103	15					
52	NOFO-1	Stillwater Reservoir	1095	5					
53	AM87-6	St. Law/Fran. Co. Line	1090	6					
54	AM87-7	Santa Clara	1080	4					
Lyon Mt Granite									
15	AM86-4	Piercefield	1075	17			1058	18	1576
16	AM86-10	Dannemora	1073	6			1052	11	
17	AM86-14	Ausable Forks, Qt-Ab	1057	10			1041	16	1350
29	CLFG	Wanakena	1113	10	1069	10	1047	10	
38	9-23-85-6	Grasshopper Hill	>1065		1049	3			
51	AM86-11	Ausable Fks., Fay GRT	1089	26	1047	2			
55	PL-3	Port Leyden			1035	4			
LOWLANDS	**Selleck**	**CCMZ**			**1047**	**10**			
Hyde School Gneiss									
23	AM86-16	Wellesley Island	1416		1172	5			1440
24	AC85-4	Gouverneur	1284						1525
25	AC87-4	Fish Creek	1236		1172	5			1210
26	AC85-5	Hyde School	1230		1172	5			1360
27	AC85-1	Reservoir Hill	ca 1172						
Antwerp Granitoid									
58	ANTG	Antwerp-Rossie	1183	7			1207	20	

ROAD LOG

0 Gathering Point: along west-bound shoulder Rt. 73 at intersection with I-87 (Exit 30).

2.3 Proceed NW along Rt. 73 to junction with Rt. 9N. Bear left on Rt. 9N to Lake Placid
5.6 Turn sharply right into the parking lot for Roaring Brook trail

Stop 1 *Roaring Brook on Giant Mt.* (located near R, Fig. 4)

The valley of Roaring Brook on the southwestern slopes of Giant Mt provides some of the finest exposures of AMCG rocks in the Adirondacks. Over a distance of ~ 1.5 km and a width of 50-100 m there occur an uncommon array of dikes, sheets and plutons of several generations and compositions that have intruded approximately parallel to the stream valley. A plausible interpretation of the association is that it represents a zone of weakness that repeatedly served as a magma conduit during the emplacement of the ca 1155 Ma AMCG suite.

From 1400’ to 2000’ the brook is underlain by a variety of anorthositic and gabbroic rocks. Near the lip of the high bridal veils falls the valley is defined by erosion of a diabase dike in the anorthosite, Slightly farther upstream z broad (~3m) irregular pyroxene-monzonite dike outcrops on the northwest bank, and clearly truncates magmatic flow foliation in the anorthosite. Coarse comb texture is visible along the dike’s margins.

Proceed upstream past several plunge pools to a steep 3-10 m cliff face. A dark, meter-wide eroded and irregular dike of orthopyroxenite is exposed at the base of the waterfall. Erosion of the dike has resulted in the stream channel and can be followed 30-40 m upstream from the cliff edge. Orthopyroxene greatly dominates the mode (90%), but some clinopyroxene, magnetite-ilmenite, and plagioclase are also present. The orthopyroxene appear to be of orthocumulate origin with narrow adcumulate overgrowths. We speculate that the origin of the dike is the result of drainage of orthopyroxene cumulates into a fracture that opened at the base of magma chamber. Several xenoliths of anorthosite are present in the dike, and locally it exhibits soft margins with the country rock anorthosite. The Mg-numbers of the pyroxenes are high (Cpx-75, Opx-65) and suggest that the dike formed early in the fractionation history of the magma.

The smooth outcrop surfaces surrounding the orthopyroxenite dike are dominated by gabbroic anorthosite transitional to gabbro. Several stages in the magmatic history of the anorthosite are recorded by crosscutting relationships. The oldest anorthosite facies are coarse-grained rafts of blue-gray andesine-labradorite anorthosite corresponding to the Marcy facies. They occur as xenoliths within as xenoliths within a medium grained, subophitic, two-pyroxene gabbro that locally grades into norite. This, in turn, is crosscut by a fine-grained gabbroic anorthosite similar to the Whiteface facies. Elsewhere in the outcrop the sequence may be reversed and attests to multiple pulses of magma; however, the coarse grained rafts are always the oldest.

Returning to the trail and proceeding uphill, we cross Roaring Brook and ascend the summit trail to the 2260’ (689m) level. Here we leave the trail and scramble downhill to water-smoothed pavement outcrops in the brook valley. The outcrops expose a spectacular intrusion breccia consisting of rounded and angular blocks (10-30 cm on average) that include coarse, white anorthosite and glassy, pink garnetiferous anorthosite, but consist mostly of gray to black, medium to fine-grained, granular pyroxene-plagioclase assemblages. These are set in a medium grained groundmass ranging from gabbroic anorthosite to garnetiferous mangerite and ferrogabbro. These matrix rocks are highly mingled and difficult to separate without the aid of staining.

A number of dark inclusions exhibit narrow (~0.5 cm), light colored layers. Traditionally these were interpreted as primary in origin and associated with a sedimentary or volcanoclastic origin (Kemp, 1921, deWaard, 1970, Mclelland et al, 1982). However, examination of stained slabs and thin sections reveals that the light layers are of syenitic composition whereas the dark layers consist of gabbro. It is common for the light, syenitic layers to be continuous with host rocks of the same composition. Moreover, the gabbroic layers contain acicular rods of orthopyroxene that, together with plagioclase, define a “fence-post” pattern (Fig. 5). The pyroxene-plagioclase layers are essentially gabbroic to dioritic in composition with subequal amounts of magnesian pyroxene and intermediate plagioclase. On the basis of chemistry and textures, we interpret the layered inclusions as igneous enclaves intruded by parallel veins of syenite and mangerite and incorporated into the mixtures of country rock magmas now constituting the breccia groundmass. The "fence-post" textures are identical to comb-textured pyroxenes in orbicular granites (McKinney, 1990) and provide compelling evidence for their igneous origin (Fig. 5).

The outcrops at Roaring Brook also contain numerous non-layered inclusions, and most of these are rich in magnesian clinopyroxene. They are interpreted as disrupted cumulates caught up by ascending AMCG magmas. None of these enclaves contain acicular pyroxene and exhibit coarse, interlocking grains. They are commonly associated with dark gray, relatively fine grained material of approximately dioritic composition and are thought to be cumulates from these magmas.

A number of the inclusions at Roaring Brook exhibit soft, lobate boundaries typical of magma commingling. Some of the anorthositic inclusions have especially well-developed borders of this sort. These features are attributed to the interaction and incomplete mixing of magmas ascending in the Roaring Brook conduit.

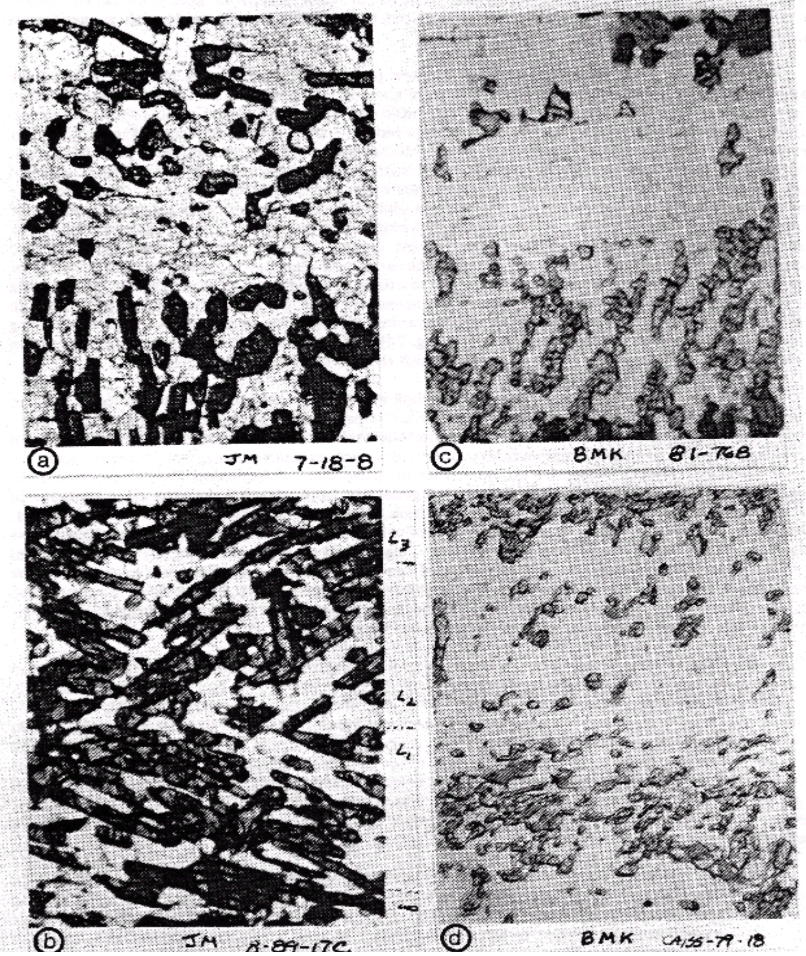


Fig. 5. Comb textures formed by acicular orthopyroxene in enclaves at Roaring Brook (a & b) compared with known com textures with acicular opx (Sierra Nevada plutons) studied by Brooks McKinney.

Table 2

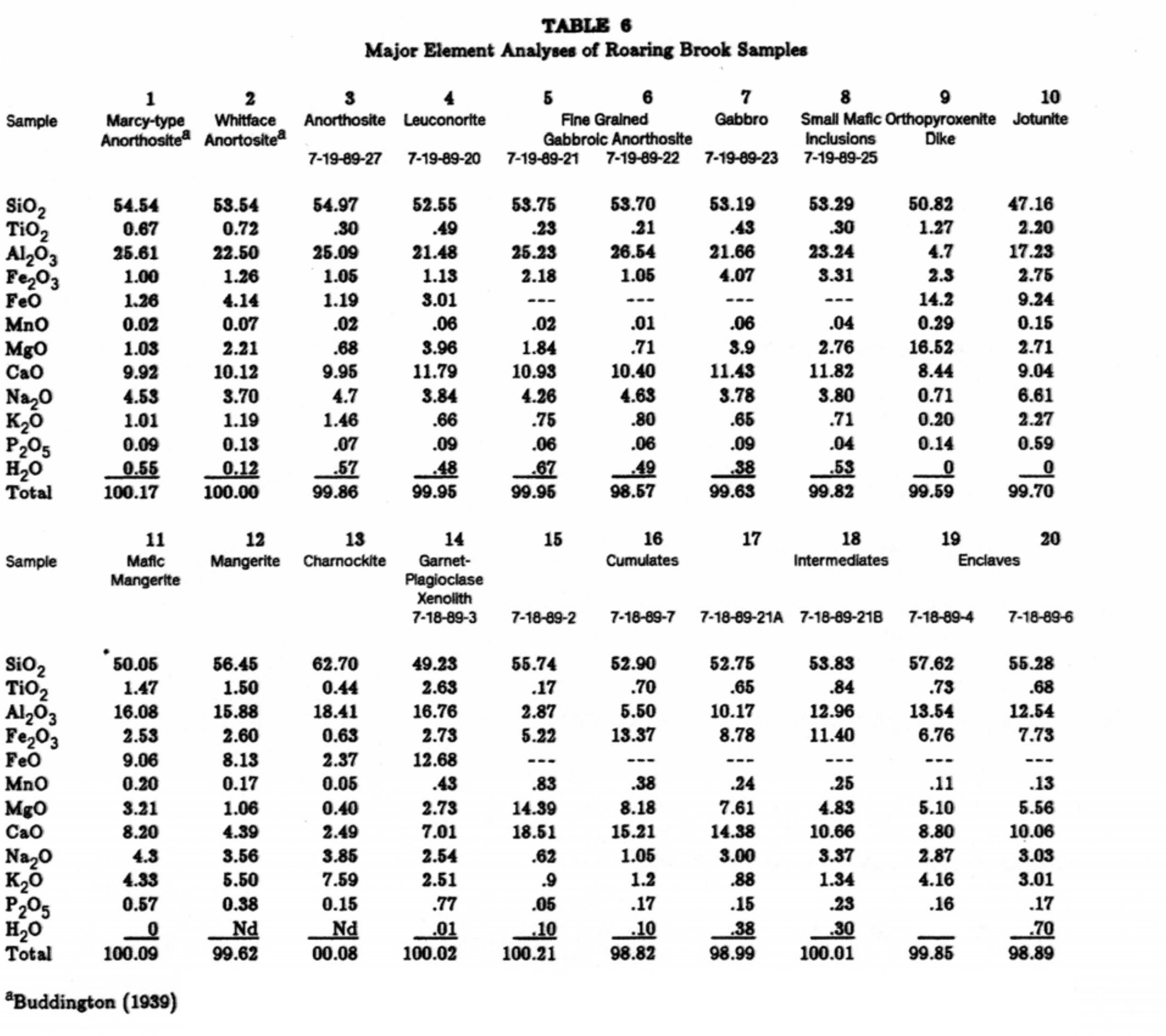


TABLE 6

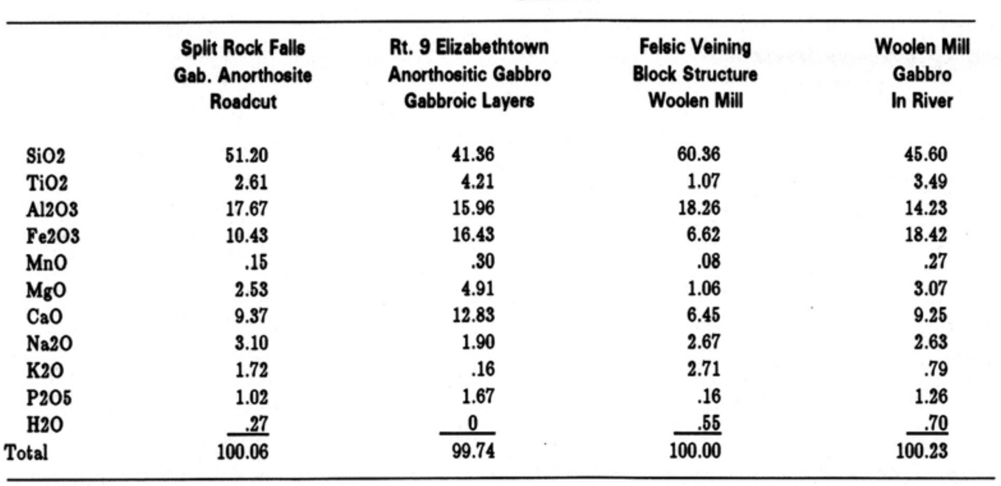
Major Element Analyses of Roaring Brook Samples

Sample	1	2	3	4	5	6	7	8	9	10
	Marcy-type Anorthosite[a]	Whitface Anortosite[a]	Anorthosite	Leuconorite	Fine Grained Gabbroic Anorthosite		Gabbro	Small Mafic Inclusions	Orthopyroxenite Dike	Jotunite
			7-19-89-27	7-19-89-20	7-19-89-21	7-19-89-22	7-19-89-23	7-19-89-25		
SiO_2	54.54	53.54	54.97	52.55	53.75	53.70	53.19	53.29	50.82	47.16
TiO_2	0.67	0.72	.30	.49	.23	.21	.43	.30	1.27	2.20
Al_2O_3	25.61	22.50	25.09	21.48	25.23	26.54	21.66	23.24	4.7	17.23
Fe_2O_3	1.00	1.26	1.05	1.13	2.18	1.05	4.07	3.31	2.3	2.75
FeO	1.26	4.14	1.19	3.01	---	---	---	---	14.2	9.24
MnO	0.02	0.07	.02	.06	.02	.01	.06	.04	0.29	0.15
MgO	1.03	2.21	.68	3.96	1.84	.71	3.9	2.76	16.52	2.71
CaO	9.92	10.12	9.95	11.79	10.93	10.40	11.43	11.82	8.44	9.04
Na_2O	4.53	3.70	4.7	3.84	4.26	4.63	3.78	3.80	0.71	6.61
K_2O	1.01	1.19	1.46	.66	.75	.80	.65	.71	0.20	2.27
P_2O_5	0.09	0.13	.07	.09	.06	.06	.09	.04	0.14	0.59
H_2O	0.55	0.12	.57	.48	.67	.49	.38	.53	0	0
Total	100.17	100.00	99.86	99.95	99.95	98.57	99.63	99.82	99.59	99.70

Sample	11	12	13	14	15	16	17	18	19	20
	Mafic Mangerite	Mangerite	Charnockite	Garnet-Plagioclase Xenolith		Cumulates		Intermediates	Enclaves	
				7-18-89-3	7-18-89-2	7-18-89-7	7-18-89-21A	7-18-89-21B	7-18-89-4	7-18-89-6
SiO_2	50.05	56.45	62.70	49.23	55.74	52.90	52.75	53.83	57.62	55.28
TiO_2	1.47	1.50	0.44	2.63	.17	.70	.65	.84	.73	.68
Al_2O_3	16.08	15.88	18.41	16.76	2.87	5.50	10.17	12.96	13.54	12.54
Fe_2O_3	2.53	2.60	0.63	2.73	5.22	13.37	8.78	11.40	6.76	7.73
FeO	9.06	8.13	2.37	12.68	---	---	---	---	---	---
MnO	0.20	0.17	0.05	.43	.83	.38	.24	.25	.11	.13
MgO	3.21	1.06	0.40	2.73	14.39	8.18	7.61	4.83	5.10	5.56
CaO	8.20	4.39	2.49	7.01	18.51	15.21	14.38	10.66	8.80	10.06
Na_2O	4.3	3.56	3.85	2.54	.62	1.05	3.00	3.37	2.87	3.03
K_2O	4.33	5.50	7.59	2.51	.9	1.2	.88	1.34	4.16	3.01
P_2O_5	0.57	0.38	0.15	.77	.05	.17	.15	.23	.16	.17
H_2O	0	Nd	Nd	.01	.10	.10	.38	.30		.70
Total	100.09	99.62	00.08	100.02	100.21	98.82	98.99	100.01	99.85	98.89

[a]Buddington (1939)

Table 3



	Split Rock Falls Gab. Anorthosite Roadcut	Rt. 9 Elizabethtown Anorthositic Gabbro Gabbroic Layers	Felsic Veining Block Structure Woolen Mill	Woolen Mill Gabbro In River
SiO2	51.20	41.36	60.36	45.60
TiO2	2.61	4.21	1.07	3.49
Al2O3	17.67	15.96	18.26	14.23
Fe2O3	10.43	16.43	6.62	18.42
MnO	.15	.30	.08	.27
MgO	2.53	4.91	1.06	3.07
CaO	9.37	12.83	6.45	9.25
Na2O	3.10	1.90	2.67	2.63
K2O	1.72	.16	2.71	.79
P2O5	1.02	1.67	.16	1.26
H2O	.27	0	.55	.70
Total	100.06	99.74	100.00	100.23

Turn left (southeast) out of parking lot onto Rt. 73

5.6 10.3 Intersection of Rt 73 & Rt. 9. Turn left (north on Rt. 9 towards Elizabethtown.

2.4 15.9 Turn right into parking area at Split Falls.

Stop 2 *Split Rock Falls* (located near 40, Fig. 5)

The roadcut across from the parking area provides good evidence for multiple intrusions of anorthositic and gabbroic rock. The dominant rock type is gabbroic anorthosite that encloses numerous xenoliths of the anorthositic suite. Subophitic textures are preserved in some of the more gabbroic xenoliths. Garnetiferous gabbro truncates foliation in some xenoliths and has, itself, a different foliations. It is thought that many of the foliations are magmatic in origin. A late mafic facies similar to that at Woolen Mill disrupts all earlier rock types. Late mafic dikes (Phanerozoic?) with well-developed slickensides cut all other lithologies.

From parking area turn right (north) on Rt. 9 to Elizabethtown.
7.7 23.6 Long outcrop on west side of Rt. 9

Stop 3 *Elizabethtown anorthositic gabbro*

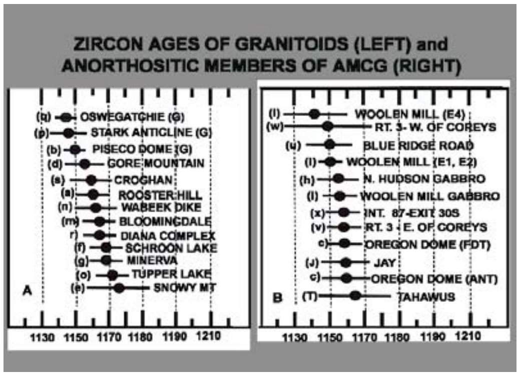
Although most of the outcrop is highly altered, it affords the opportunity to see the effects of Ottawan deformation on AMCG rocks that are situated near the outer margins of the Marcy Massif. Most of the outcrop consists of somewhat gneissic anorthositic gabbro. Some small calcsilicate inclusions consist of grossularite, diopside, and wollastonite. Large cm-scale garnets appear to truncate foliation and may have grown under static conditions. Large black clots of hornblende contain remnant pyroxene cores and may represent deformed, metamorphosed giant pyroxenes.

1.3 24.9 Continue north on Rt. 9 until junction with Rt. 9N. Turn left (west) on Rt. 9N
1.1 26 Pull off into dirt parking area on right and across from large, dark roadcut.
Stop 4 *Woolen Mills Anorthosite and Ferrogabbro* (located near 40, Fig.5)

The large roadcut shows anorthosite intruded by a dark, reddish-brown, fine-grained rock known as the Woolen Mill Gabbro (1154 ± 9 Ma) for the mill that once existed in the stream across the road. It is a clinopyroxene-garnet-oligoclase granulite with considerable opaque oxides and apatite and minor K-feldspar and quartz. Prior to metamorphism, the granulite was a late ferrodiorite representing residual mafic liquids filter-pressed from the anorthosite. The outcrop was used by deWaard (1965) to establish his clinopyroxene-garnet subfacies of the granulite facies that marks the transition to higher pressures, garnet granulites, and ultimately the eclogite facies.

Across the road from the granulite, a variety of anorthositic rocks (1155 ± 8 Ma) are exposed in the streambed. At the west end of the water-polished outcrops, Woolen Mill gabbro clearly intrudes the anorthosite. However, note an inclusion of gabbro in the anorthosite indicative of coeval relationships. Note the "block structure" where blocks of earlier anorthosite have been broken up and intruded by later magmatic pulses.

Fig. 6



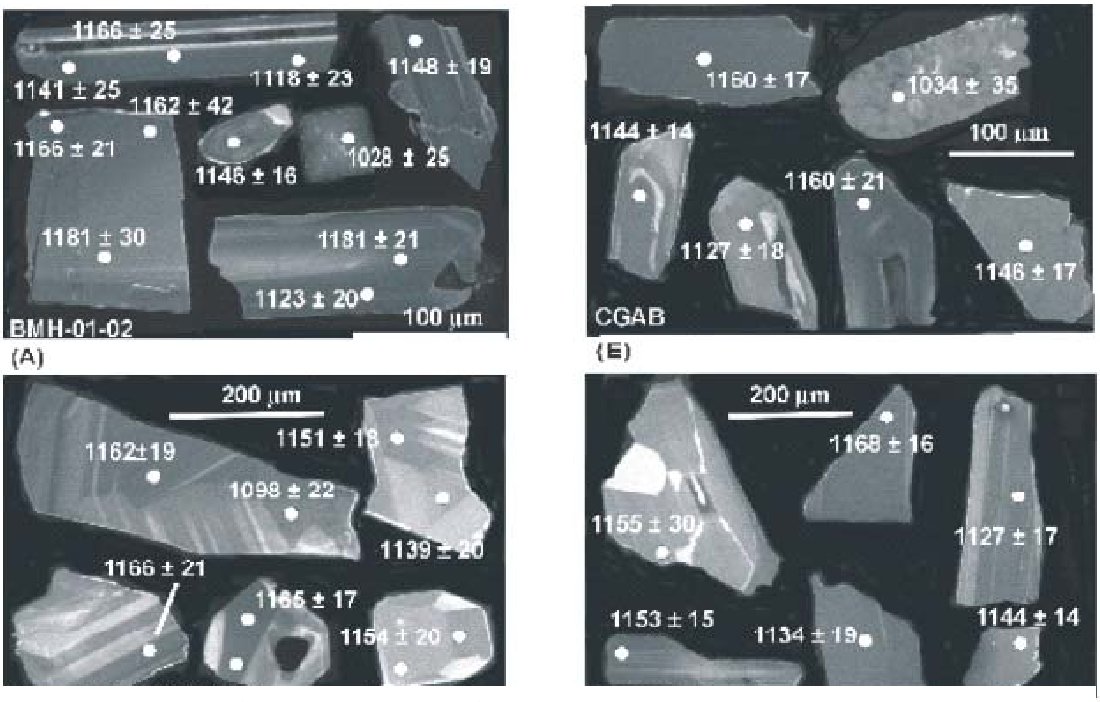


Fig. 7a. CL images of SHRIMPed zircons from Adirondack anorthosite showing ages of spots

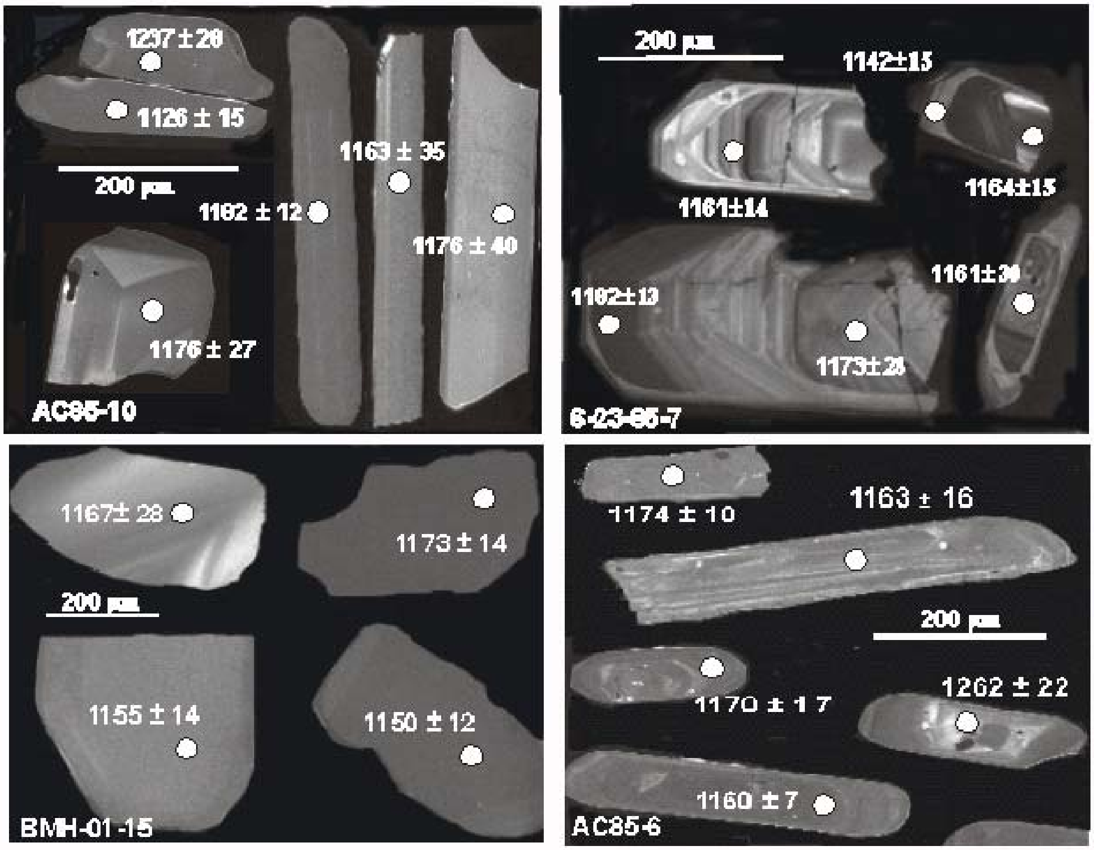


Fig. 7b. CL images of SHRIMPed zircons from Adirondack granitoids showing ages of spots.

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