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DISTINGUISHING GRENVILLIAN BASEMENT FROM PRE-TACONIAN COVER ROCKS IN THE NORTHERN APPALACHIANS

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ABSTRACT. Distinguishing Grenvillian basement rocks from pre-Taconian cover sequences in the Appalachians is a first-order problem essential for accurate structural interpretations. The Cavendish Formation in southeastern Vermont presents a classic example of this problem. Doll and others (1961) showed the Cavendish Formation as younger than the Middle Proterozoic Mount Holly Complex but older than the lithologically similar Cambrian Tyson and Hoosac Formations. More recently, the name Cavendish Formation has been informally abandoned, and its metasedimentary units have been mapped as the Tyson and Hoosac Formations of Late Proterozoic to Cambrian age. In a radical departure from these interpretations, Ratcliffe and others (1997) reassigned metasedimentary rocks of the Cavendish Formation to the Mount Holly Complex based on an inferred intrusive relationship between them and a 1.42 Ga tonalite. This new age assignment, if correct, requires a completely new structural interpretation of the region.

SHRIMP and Pb evaporation ages of detrital zircons extracted from a quartzite layer from Cavendish Gorge near the proposed intrusive contact with the tonalite constrain the time of deposition of the Cavendish Formation. Grain shapes of the zircons vary from euhedral to nearly spherical. Virtually all the grains have pitted surfaces and show at least some rounding of edges and terminations; grains exhibit oscillatory zoning typical of zircons that crystallized from a magma. Single-grain Pb evaporation analyses of ten zircons and SHRIMP analyses of 15 zircons all yield ages less than 1.42 Ga. Seven of the grains are consistent with derivation from the Bull Hill Gneiss that postdates the Grenville orogenic cycle and predates deposition of the Cavendish Formation. Thus, the metasedimentary units of the Cavendish Formation should not be assigned to the Mount Holly Complex.

INTRODUCTION

Rocks older than about 1.03 Ga in the Appalachians record effects of the Grenville orogenic cycle (Easton, 1986; McLelland and others, 1996). At the close of the Precambrian, continental rifting created a new passive margin along the eastern border of Laurentia, with Grenvillian rocks forming the basement on which Late Proterozoic to Ordovician sedimentary cover rocks were deposited. In western New England, the Taconian orogeny deformed and metamorphosed rocks of the continental margin as young as approx. 455 Ma. Late Ordovician to Early Devonian (that is, post-Taconian) intrusive, volcanic, and sedimentary rocks, along with both older sequences, were deformed and metamorphosed during the Acadian orogeny. Recent work shows that the Acadian orogeny was complex and spanned a significant time interval (Robinson and others, 1998; Bradley and others, 1998). In western Massachusetts, south of our study area, the Acadian orogeny deformed rocks dated at 376 ± 4 Ma but not the 373 ± 5 Ma Williamsburg Granodiorite (Karabinos and Williamson, 1994).

Clearly, a first-order problem in interpreting the structural and tectonic history of this complex region is to assign rocks correctly to one of three recognized sequences: Grenvillian basement, pre- and syn-Taconian cover, or post-Taconian cover. U-Pb dating of zircons has established the ages of many metaigneous rocks in Vermont (Karabinos and Aleinikoff, 1990; Aleinikoff and Karabinos, 1990; Ratcliffe and others, 1991; Karabinos and others, 1998). However, because fossils are exceedingly scarce,

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previous age assignments for metasedimentary rocks were commonly based on long-range, sometimes tenuous, correlations with fossiliferous strata. Many of these age assignments are now supplemented by radiometric dating of cross-cutting igneous rocks, metamorphic minerals, and detrital zircons. Lower age constraints may also be established by evidence that a unit experienced one of the documented orogenies. However, despite extensive study, the assignment of some units to one of the three major sequences remains controversial.

An ongoing problem in southern Vermont is distinguishing Grenvillian basement (the Mount Holly Complex of Doll and others, 1961) from pre-Taconian cover rocks. Doll and others (1961) assigned to the Cambrian (?) Cavendish Formation a diverse group of metasedimentary and metaigneous rocks that directly overlie Grenvillian basement. Doll and others (1961) included the Cavendish Formation in the pre-Taconian cover sequence stratigraphically below the Cambrian Tyson and Hoosac Formations (fig. 1). The metasedimentary units in the Cavendish Formation were later reassigned to the Tyson and Hoosac Formations by Thompson and others (1977), Karabinos (1984a), and Thompson and others (1990), and the age assignment of these formations was changed to Late Proterozoic to Cambrian. This new interpretation was based on the recognition of thrust faults that repeat distinctive lithologies. Another difficulty with the Cavendish Formation, as defined by Doll and others (1961), emerged when Karabinos and Aleinikoff (1990) used U-Pb zircon dating to show that the distinctive augen gneiss member, the Bull Hill Gneiss, forms a major post-Grenvillian plutonic suite that intruded the Mount Holly Complex at about 965 to 945 Ma. Thus, the Bull Hill Gneiss member must be substantially older than the schist and impure marble units in the Cavendish Formation of Doll and others (1961), assuming that correlation of these metasediments with the Late Proterozoic to Cambrian Tyson and Hoosac Formations is correct.

Most workers informally abandoned the term "Cavendish Formation," because its metasedimentary members were reassigned to other formations, and its metaigneous member was reinterpreted as a post-Grenvillian intrusive suite stratigraphically unrelated to the metasedimentary units (Karabinos and Aleinikoff, 1990). However, in a major departure from earlier interpretations, Ratcliffe (1994) and Ratcliffe and others (1996, 1997) revived the name Cavendish Formation and assigned its metasedimentary units to the Mount Holly Complex. This new interpretation, if correct, requires a dramatic change in structural reconstructions of the Green Mountain massif and Chester dome (Ratcliffe, 1995).

To test this new age assignment, we separated detrital zircons from a quartzite layer from Cavendish gorge, the type locality of what Richardson (1929) called the Cavendish Schist. This is also the location where Ratcliffe and others (1996, 1997) obtained a 1.42 ± 0.02 Ga age on a tonalite that they interpreted as cutting the Cavendish Formation. We analyzed single zircons by both the Pb evaporation method and by the sensitive high resolution ion microprobe (SHRIMP). On the basis of these ages, the Cavendish Formation must be younger than the Grenvillian basement. To avoid confusion at this stage of the controversy, we continue to refer to these rocks as the Cavendish Formation, but we hope that soon this name will be abandoned.

STRATIGRAPHY

Richardson (1929) used the term "Cavendish Schist" for quartz-biotite-plagioclase schist in Cavendish Gorge and on Hawks Mountain. He used the name "Gassetts Schist" for a garnet-muscovite-staurolite schist in the same region that is best exposed in roadcuts just west of the village of Gassetts. The exact distributions of these units are difficult to determine from his maps (Richardson, 1929, p. 210-211). Billings and others (1952) concluded that these rocks are part of the Grenvillian basement. Later, Doll and others

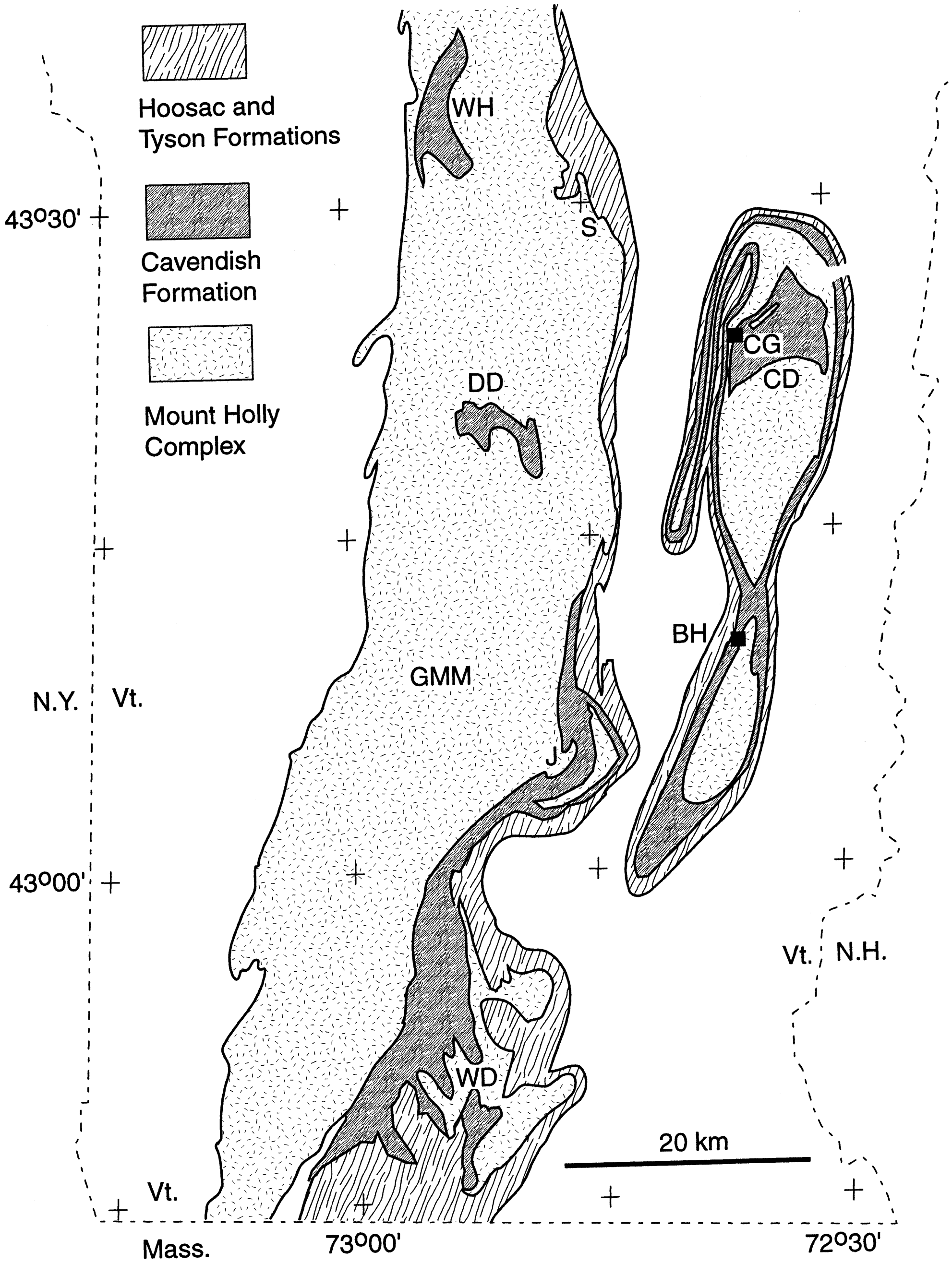

Fig. 1. Simplified geologic map of southern Vermont showing distribution of the Middle Proterozoic Mount Holly Complex, the Cavendish Formation, and the Late Proterozoic to Cambrian Hoosac and Tyson Formations from Doll and others (1961). Abbreviations are: BH–Bear Hill, CD–Chester Dome, CG–Cavendish gorge, DD–Devils Den, GMM–Green Mountain massif, J–Jamaica, S–Sherburne, WD–Wilmington dome, WH–Wilcox Hill.

(1961) created the unit Cavendish Formation, which included these rocks and others, as a repository for rocks whose stratigraphic affinity was uncertain at the time of the compilation of the geologic map of Vermont but were best included in the pre-Taconian cover sequence (that is, post-Grenvillian). Mostly these rocks are structurally between the Mount Holly Complex and the Hoosac Formation, although two large isolated exposures exist within the Mount Holly Complex in the Green Mountain massif (fig. 1). Doll and others (1961) subdivided the Cavendish Formation into three units: (1) the Readsboro Member, composed of quartz-muscovite-biotite-chlorite-plagioclase schist together with quartz-muscovite-paragonite-chloritoid-garnet schist, essentially the Cavendish and Gassetts Schists of Richardson (1929); (2) the Bull Hill Gneiss, a quartz-plagioclase-microcline-biotite gneiss; and (3) a unit composed of buff dolomitic marble, calcitic marble, and impure marble containing actinolite and diopside. The carbonate-rich unit commonly contains layers of vitreous quartzite. Doll and others (1961) explicitly stated that some of the rocks in this formation may be equivalent to the Tyson Formation or may belong to the Mount Holly Complex. Skehan (1961) also suggested that rocks in southern Vermont that he mapped as Heartwellville Schist, Sherman Marble Member of the Readsboro Formation, Readsboro Schist, and Searsburg Conglomerate, which were included in the Cavendish Formation by Doll and others (1961), could all be structural repetitions of the Tyson and Hoosac Formations or other units in the pre-Taconian cover sequence.

Correlation of the metasedimentary units in the Cavendish Formation with other formations in the post-Grenvillian cover sequence has been accepted for more than 20 yrs. Thompson and others (1977) informally used the name Gassetts Schist in a study of a garnet-muscovite-staurolite schist located along route 103 near Gassetts, Vermont, but they correlated it with the Hoosac Formation. Karabinos (1984a,b) and Thompson and others (1990) interpreted some rocks shown as the Marble and Readsboro Members of the Cavendish Formation by Doll and others (1961) as the Late Proterozoic to Cambrian Tyson and Hoosac Formations, respectively, structurally repeated by thrust faults. Ratcliffe (1997), following Karabinos (1984a), mapped rocks near Jamaica, Vermont, shown as Cavendish Formation by Doll and others (1961), as the Hoosac Formation (fig. 1).

Quartzite and marble lithologies of the Cavendish Formation in the Chester dome are strikingly similar to discontinuously exposed quartzite and marble in the uppermost part of the Tyson Formation along the east margin of the Green Mountain massif, especially in Sherburne, Vermont (Karabinos and Thompson, 1997). In both areas the quartzite and marble are structurally overlain by a distinctive quartz-muscovite-biotite schist containing abundant plagioclase porphyroblasts. This schist was called the Readsboro Member of the Cavendish Formation in the Chester dome and the Hoosac Formation on the east side of the Green Mountain massif by Doll and others (1961). In both areas an iron-rich zone up to 1 m thick is developed at the stratigraphic top of the marble, just below the contact with the plagioclase schist. This distinctive sequence of lithologies is also found in the Cavendish Formation in the Devils Den area in the Green Mountain massif and near Jamaica, Vermont (Karabinos and Thompson, 1997).

The metaigneous member of the Cavendish Formation was studied by Karabinos and Aleinikoff (1990), who presented U-Pb zircon ages showing that the Bull Hill Gneiss formed between ~965 to 945 Ma. Thus, these rocks are too young to have experienced the intense Middle Proterozoic deformation and metamorphism of the Ottawan phase of the Grenville orogenic cycle (older than ~1.03 Ga in the nearby Adirondacks; McLelland and others, 1996) but are too old to be part of the Late Proterozoic to Cambrian cover sequence. They are probably part of a widely distributed post-Grenvillian plutonic suite (Gower and others, 1991). If correlation of the metasedimentary units in the

Cavendish Formation with the Tyson and Hoosac Formations is correct, there can be no stratigraphic continuity between them and the Bull Hill Gneiss.

Ratcliffe (1994, 1995) revived the name Cavendish Formation for some of the metasedimentary units included in the Cavendish Formation as defined by Doll and others (1961). Not included by him were the Bull Hill Gneiss and exposures of metasedimentary rocks mapped by Doll and others (1961) as the Cavendish Formation around the Wilmington dome and in the Jamaica, Vermont, area. Ratcliffe (1994, 1995) assigned his redefined Cavendish Formation to the Mount Holly Complex on the basis of his interpretation of the map distribution of lithologies. He believed that calc-silicate rock, quartzite, and schist exposed in Cavendish gorge and elsewhere in the Chester dome were intruded by the Felchville Gneiss of the Mount Holly Complex. Ratcliffe and others (1996, 1997) further argued that the Cavendish Formation must be older than 1.42 Ga based on a SHRIMP age for the Felchville Gneiss. The reassignment of the Cavendish Formation to Grenvillian basement demands a completely new interpretation of the structure of the Chester dome, which has appeared in recently published quadrangle maps (Ratcliffe, 1995).

It is important to note, however, that the interpretation of an intrusive contact between the Felchville Gneiss and the Cavendish Formation is based on map-scale patterns rather than actual field observations. There are no xenoliths of Cavendish Formation in the tonalite, nor are there apophyses of tonalite in the Cavendish Formation. In contrast, xenoliths of distinctive lithologies typical of the Cavendish Formation are abundant in syntectonic Acadian plutons in the Chester dome (Bebout and Rosenfeld, 1993). The contact between the tonalite and the Cavendish Formation, where best exposed in Cavendish gorge is highly sheared, hence we feel that a more plausible explanation for the truncation of the metasedimentary units is a fault.

A serious challenge to assigning the Cavendish Formation to Grenvillian basement is that the rocks lack evidence of the intense sillimanite-grade metamorphism experienced by the Mount Holly Complex. A distinctive lithology in the Cavendish Formation is the so-called Gassetts Schist, which has been the subject of numerous metamorphic studies (Rosenfeld, 1968; Thompson and others, 1977; Karabinos, 1984b; Cook and Karabinos, 1988; Chamberlain and Conrad, 1993; Vance and Holland, 1993). Garnets in the Gassetts schist commonly reach 2 cm in diameter, contain abundant inclusions, and show textural as well as chemical evidence for two distinct periods of growth (Rosenfeld, 1968; Karabinos, 1984b). According to all the studies cited above, the second stage of garnet growth clearly is Acadian. Rosenfeld (1968) suggested that the first episode of metamorphism is Taconian, but possibly it too is Acadian. Cook and Karabinos (1988) studied this unit throughout southeastern Vermont over a wide range of metamorphic grades and showed that, from the Chester dome west to the Green Mountain massif and south to the Massachusetts border, these rocks record a consistent metamorphic history that can be correlated with the development of deformational fabrics. None of the hundreds of samples of Gassetts Schist and similar lithologies studied by Karabinos and his students shows evidence of an early sillimanite-grade event. Therefore, if these rocks are part of the Grenvillian basement, all traces of the Middle Proterozoic high-grade metamorphism must have been erased before Paleozoic metamorphism occurred. The important point here is that all the rocks mapped as the Readsboro Member of the Cavendish Formation by Doll and others (1961) share a common deformational and metamorphic history, with the notable exception of exposures near Wilcox Hill and Bear Hill (fig. 1) as discussed below.

Lithologically and texturally identical rocks are mapped as the Cavendish Formation of the Mount Holly Complex in the Chester dome (Ratcliffe, 1995) and as part of the Hoosac Formation in the Wilmington dome (Ratcliffe and others, 1992) and near Jamaica, Vermont (Ratcliffe, 1997). It seems unlikely to us that such similar packages of rocks can belong to two such dramatically different sequences as the Grenvillian basement and the pre-Taconian cover.

SAMPLE DESCRIPTION AND ANALYTICAL METHODS

The sample used for geochronology (2921, fig. 2) is from the Cavendish gorge section of the Black River in Cavendish, Vermont, approx 50 m south of the power generating station. Here, interlayered calcsilicate rock, calcitic marble, and vitreous quartzite define a recumbent fold only a few meters from the contact with the 1.42 Ga tonalite mapped by Ratcliffe (1995) as Felchville Gneiss of the Mount Holly Complex.

Our sample (2921) was collected from a vitreous quartzite layer within the recumbent fold. The zircon population contains grains having euhedral outlines, rounded edges, and pitted faces; length-to-width ratios of 4 are common (fig. 3A). Also present are

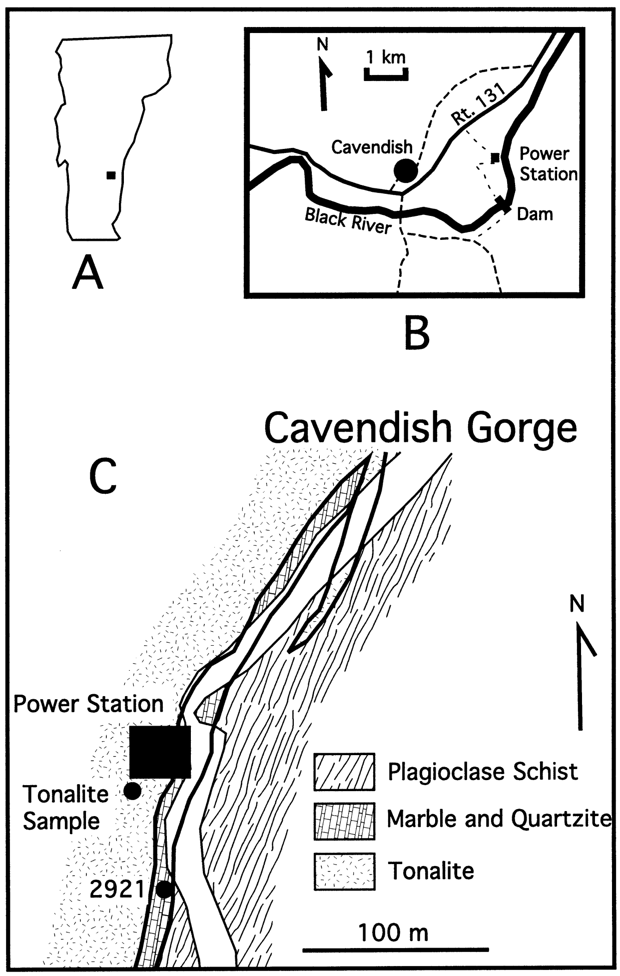

Fig. 2. Map of Cavendish gorge. (A) Approximate location of Cavendish, Vermont. (B) Location of Cavenish gorge between Dam and Power Station. (C) Geologic sketch, based on unpublished mapping by Karabinos, showing distribution of tonalite (Felchville Gneiss) belonging to the Mount Holly Complex and metasedimentary rocks of the Cavendish Formation. Locations of geochronological samples 2921 and tonalite (Ratcliffe and others, 1997) are marked by solid circles.

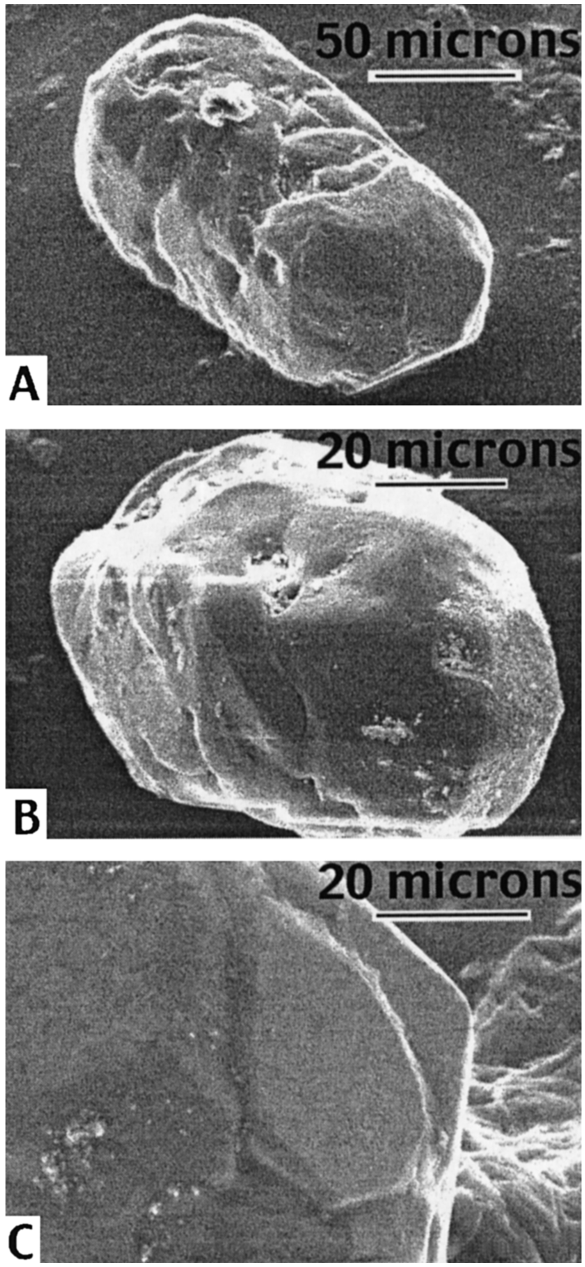

Fig. 3. Scanning electron microscope images of zircons from the Cavendish Formation. (A) Grain with euhedral outline, rounded edges, and pitted faces. (B) Oval grain with heavily pitted surfaces. (C) Rare grain with faceted surfaces that may reflect limited metamorphic overgrowth.

oval to nearly spherical grains with heavily pitted surfaces (fig. 3B). Rarely, grains have faceted surfaces that may indicate limited overgrowth of zircon during metamorphism (fig. 3C). Cathodoluminescence (CL) images of selected grains show oscillatory zoning patterns typical of zircon that grew in a magma (fig. 4). Very thin rims can be attributed

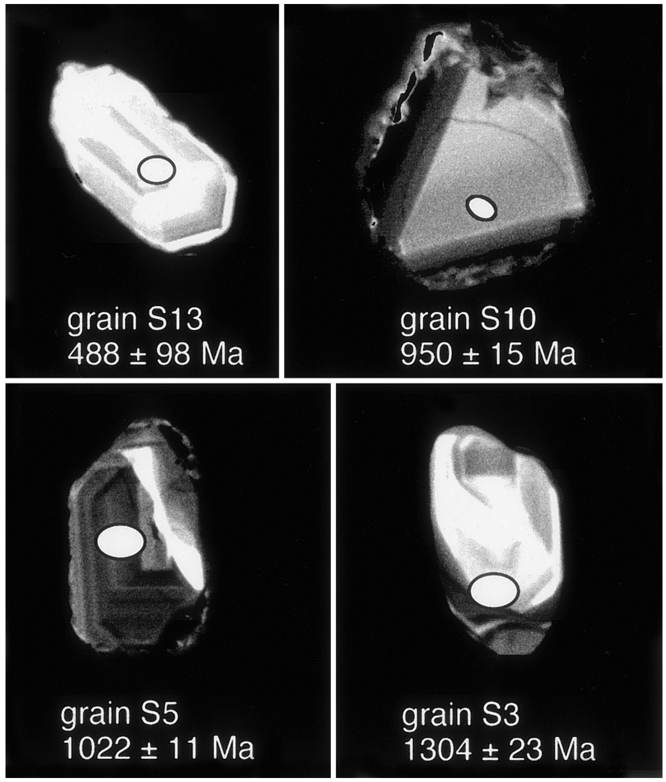

Fig. 4. Cathodoluminescence images of zircons from the Cavendish Formation. Ovals (25 µm) show location of SHRIMP U-Pb analyses. Oscillatory zoning patterns are typical of igneous zircons.

to metamorphic overgrowths. Our interpretation is that these zircons were eroded from igneous rocks and deposited as detrital grains in the sandstone protolith of the quartzite, with very limited additional growth of zircon occurring during subsequent metamorphism(s).

Pb evaporation analyses were performed at Brown University following the methods outlined by Kober (1986, 1987) and modified by Karabinos and Gromet (1993). Double filament assemblies were mounted into a Finnigan Mat 261 thermal ionization mass spectrometer, and isotope ratios were measured by peak-hopping into an electron multiplier fitted with a 10^8 ohm feedback resistor. Data were collected in blocks of 10 scans of the mass spectrum.

Preconditioning of grains occurred at approx 1450°C for 30 min. Subsequent evaporation at temperatures ranging from 1550° to 1700°C caused Pb to plate onto the opposing filament. This Pb was re-evaporated and ionized at 1100° to 1300°C, yielding typical ion signals of 2.5-250 $\times 10^{-15}$ amperes of ^{206}Pb. All isotope ratios were corrected for a multiplier mass bias of 0.225 percent per amu, determined by comparison of repeated peak-hop analyses of NBS SRM 982 in the multiplier with those in a Faraday cup. No corrections were applied for mass fractionation. Common Pb corrections used age-appropriate model Pb values from Stacey and Kramers (1975). All grains were analyzed at successively higher evaporation temperatures until they no longer produced a measurable Pb signal.

SHRIMP data were obtained using the SHRIMP II ion microprobe at the Research School of Earth Sciences, Australian National University, following the methods described in Compston and others (1984) and Williams and Claesson (1987). Zircon samples were sprinkled onto double stick tape, mounted in epoxy, ground with 1500 grit sand paper, and polished with 6 and 3 μm diamond paste. Analyzed grains were randomly selected from a small area on the mount. The analyses were conducted using a primary beam of oxygen ions that excavated a crater approx 25 μm in diam and 0.5 μm deep. Isotopic data were collected in blocks of four scans through the mass spectrum. Because the focus of this study was to determine if the Cavendish Formation contains zircons younger than ~1.4 Ga, we only needed to analyze 15 grains, in contrast to provenance studies using detrital zircons that routinely analyze 50 to 100 grains. Isotopic ratios were measured on the standard zircon (AS3, 1099-Ma anorthositic gabbro from the Duluth Complex; Paces and Miller, 1993) every fourth analysis to calibrate fractionation of Pb/U. All grains except S13 are dated using the $^{207}Pb/^{206}Pb$ age (table 1) because the uncertainties in the $^{206}Pb/^{238}U$ ages are quite large due to the limited number of standards analyzed and the minimal number of cycles per analysis.

RESULTS

$^{207}Pb/^{206}Pb$ evaporation ages of the zircons range from 943 to 1290 Ma (table 2, fig. 5). Ideally, individual grains are evaporated at more than one temperature to test for isotopic heterogeneity. Because 5 of the 10 grains in this study gave usable data at only one evaporation temperature, it is not possible to verify that the radiogenic Pb from these grains was derived from a single homogeneous domain. However, the ages of these 5 grains (E-1, E-5, E-6, E-7, and E-9) are very similar to other Pb evaporation and SHRIMP ages from this sample. Therefore, we believe it is reasonable to use these ages

TABLE 1

SHRIMP isotopic data for the Cavendish Formation, Chester Dome, Vermont

Sample	Measured $^{204}Pb/^{206}Pb$	Measured $^{206}Pb/^{207}Pb$	%common ^{206}Pb	U(ppm)*	Th/U	$^{207}Pb^{**}/^{206}Pb$	err***	Age****	err§
S1	0.00014	0.075	0.24	50	1.25	0.0731	2.8	1016	56
S2	0.000097	0.075	0.17	550	0.11	0.0738	1.1	1035	23
S3	0.0001	0.086	0.18	330	0.71	0.0845	1.2	1304	23
S4	0.0000078	0.075	0.01	320	0.28	0.0752	0.9	1075	17
S5	0.000023	0.074	0.04	1420	0.29	0.0733	0.5	1022	11
S6	0.000021	0.084	0.04	740	0.30	0.0838	0.6	1287	11
S7	0.000025	0.074	0.04	580	0.20	0.0739	0.8	1038	17
S8	0.00027	0.074	0.47	140	0.25	0.0705	3.3	944	67
S9	0.00012	0.08	0.21	180	0.26	0.0782	2.2	1152	43
S10	0.00008	0.072	0.14	890	0.35	0.0708	0.7	950	15
S11	0.00046	0.075	0.78	100	1.31	0.0686	4.7	887	98
S12	0.0001	0.075	0.18	660	0.42	0.0732	1.1	1019	22
S13	0.0019	0.066	3.33	130	0.49	0.0769	20.6	488	98
S14	0.00069	0.079	1.19	100	0.92	0.0695	7.7	913	159
S15	--	0.071	--	210	0.31	0.0721	1.5	988	31

* ±10-20%
** Corrected for common Pb using Stacey and Kramers (1975) values. Ratio for grain S13 is $^{206}Pb/^{238}U$.
*** 1-sigma percent errors.
**** $^{207}Pb/^{206}Pb$ ages except grain S13 which is $^{206}Pb/^{238}U$ age.
§ 1-sigma absolute errors.

TABLE 2

Pb evaporation data for the Cavendish Formation, Chester Dome, Vermont

Sample 2921 grain#	Plating Temp	$^{206}Pb/^{204}Pb$	$^{206}Pb/^{208}Pb$	$^{207}Pb/^{206}Pb$	$^{207}Pb§/^{206}Pb$	Age § (Ma)	Percent Uncertainty†	Weighted Average Age ¥
E 1	1525	3539	36.23	0.07455	0.07050	943	1.52	943 +/- 14
E 2	1450	9295	9.42	0.07273	0.07119	963	1.71	968 +/- 8
	1500	21971	5.86	0.07202	0.07137	968	0.38	
E 3	1480	14620	32.29	0.07276	0.07178	980	0.63	980 +/- 4
	1480	14928	31.72	0.07341	0.07245	999	0.84	
	1480	12473	31.40	0.07289	0.07174	979	0.28	
	1500	27655	33.37	0.07247	0.07196	985	0.61	
	1500	16962	33.32	0.07260	0.07176	979	0.43	
	1530	14737	33.89	0.07278	0.07181	981	1.41	
E 4	1460	7582	5.22	0.07300	0.07111	959	0.42	988 +/- 27
	1480	8587	4.20	0.07385	0.07219	984	1.05	
	1500	6855	3.38	0.07375	0.07166	977	1.70	
	1500	8973	3.38	0.07389	0.07230	995	1.29	
	1525	6945	2.88	0.07519	0.07313	1018	0.94	
E 5	1500	6201	7.01	0.07521	0.07291	1012	1.72	1012 +/- 25
	1500	5950	7.33	0.07504	0.07264	1004	1.48	
	1500	6553	3.96	0.07464	0.07246	999	0.75	
E 6	1500	2420	7.58	0.08007	0.07418	1047	0.95	1055 +/- 11
	1500	2707	7.55	0.07988	0.07461	1058	0.63	
E 7	1520	2001	5.88	0.08411	0.07700	1122	2.89	1122 +/- 32
E 8	1450	7804	15.72	0.07854	0.07672	1114	0.94	1128 +/- 8
	1460	6766	16.02	0.07771	0.07753	1135	0.45	
	1470	58200	15.57	0.07767	0.07743	1133	0.09	
	1490	11166	14.83	0.07844	0.07716	1126	0.32	
	1510	34078	13.83	0.07765	0.07732	1130	1.67	
E 9	1500	2145	8.62	0.08556	0.07896	1171	1.52	1171 +/- 18
E 10	1480	3553	9.17	0.08506	0.08108	1224	2.37	1290 +/- 11
	1500	5096	8.19	0.08660	0.08384	1289	0.48	
	1500	4561	8.17	0.08715	0.08406	1294	0.85	

§ Corrected for common Pb
† Uncertainties at 68% confidence level.
¥ Uncertainties at 95% confidence level.

from single-temperature evaporations to help constrain the age of the Cavendish Formation.

SHRIMP ages of 15 zircons are mostly similar to ages determined by the Pb evaporation method (table 1; fig. 5). Ages range from 488 ± 98 to 1304 ± 23 Ma; seven of the ages are between 1.0 and 1.2 Ga.

Figure 5 shows that all the Pb evaporation and SHRIMP ages of zircons from the Cavendish Formation are younger than the 1.42 Ga age of the Felchville Gneiss. Significantly, there is considerable overlap between our relatively small sample of single

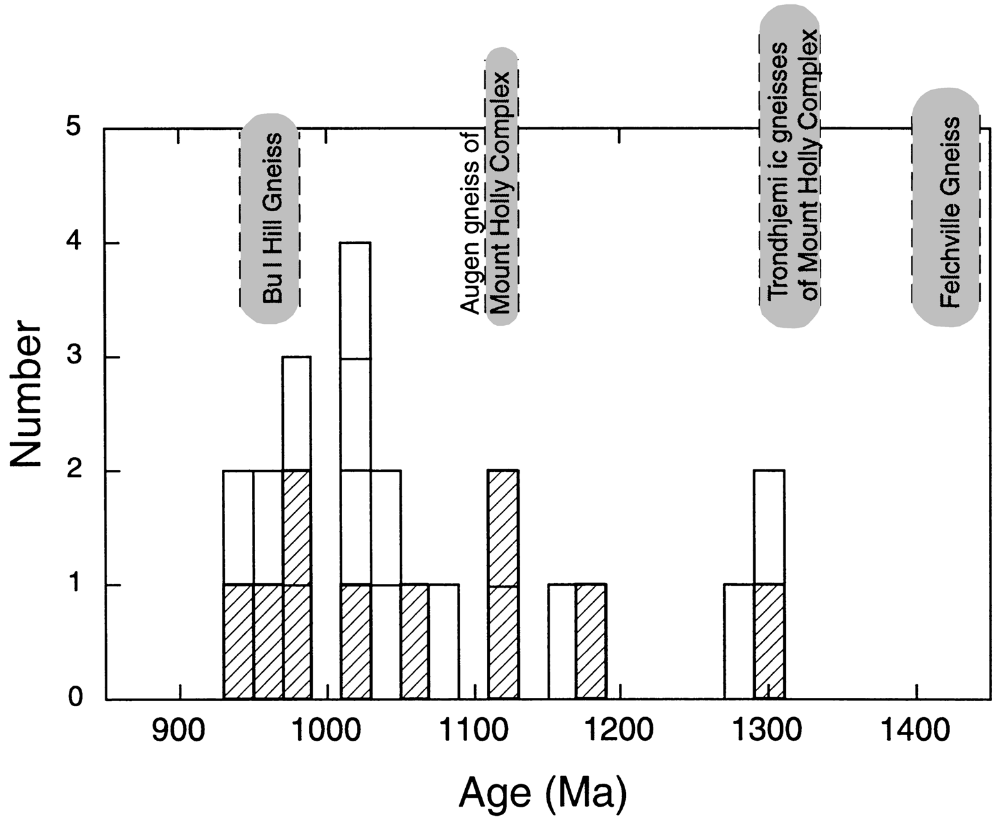

Fig. 5. Histogram of Pb evaporation analyses (diagonal lines) and SHRIMP analyses (unpatterned) from single zircons of the Cavendish Formation. Bins are 20 my. Shaded regions at top of diagram show the age ranges of the Bull Hill Gneiss and Augen gneiss of the Mount Holly Complex (Karabinos and Aleinikoff, 1990), trondhjemitic gneisses of the Mount Holly Complex (Ratcliffe and others, 1991), and the Felchville Gneiss from Cavendish Gorge (Ratcliffe and others, 1997) for comparison with the detrital zircon ages. SHRIMP ages with analytical uncertainties greater than 10 percent (table 2) were excluded from the plot.

zircon ages and three well-documented igneous suites in the Green Mountain massif in Vermont (fig. 5): (1) the Bull Hill Gneiss (965 ± 5 to 945 ± 5 Ma, Karabinos and Aleinikoff, 1990), (2) the augen gneiss of the Mount Holly Complex (1121 ± 1 to 1119 ± 3 Ma, Karabinos and Aleinikoff, 1990), and (3) trondhjemitic gneisses of the Mount Holly Complex (1356 ± 3 to 1308 ± 10 Ma, Ratcliffe and others, 1991). The numerous ages in the range of 1.0 to 1.1 Ga are similar to the ages of metaigneous rocks in the Adirondack Mountains (Easton, 1986) and the Green Mountain massif (unpublished data of J.N. Aleinikoff). The single zircon ages consistent with derivation from the Bull Hill Gneiss are significant, because they demonstrate that the metasedimentary units of the Cavendish Formation postdate the intense Middle Proterozoic (~1.03 Ga) deformation and metamorphism experienced by Grenvillian basement rocks in the region (McLelland and others, 1996).

The age of grain S-13 (488 ± 98 Ma, table 1) is consistent, within the large uncertainty, with the presumed age of deposition of the Cavendish Formation, if this unit is correlative with the Late Proterozoic to Cambrian Hoosac Formation. This grain is somewhat elongate, anhedral, with rounded edges and tips. CL imaging of grain S-13 reveals oscillatory zoning typical of igneous zircon (fig. 4). There is little to distinguish this grain from others in the sample. On the basis of external morphology and CL zoning, we conclude that grain S-13 is not metamorphic in origin. Thus, its age may help constrain the time of deposition of the Cavendish Formation (that is, sedimentation postdates the youngest detrital grain). However, we are cautious about placing too much emphasis on the data from grain S-13, because it is the only analyzed zircon having this age and because of its large uncertainty. It is unlikely that this grain is a contaminant from the mineral separation process because: (1) the laboratory is stringently maintained for cleanliness, and (2) other samples processed at about the same time with similar ages contained euhedral (that is non-abraded) zircons. Analyses of many more zircons will be necessary to evaluate the significance of the age of grain S-13.

We believe that the Pb evaporation and SHRIMP zircon ages reported here represent the time of crystallization of igneous rocks that were eroded to supply zircons to the sandstone protolith of the quartzite layer. Our interpretation of the age of the Cavendish Formation would be incorrect if the zircons grew entirely during metamorphism, had significant metamorphic overgrowths, or were isotopically reset during one or more thermal events. However, external morphology and concentric oscillatory zoning patterns of the zircons (figs. 3 and 4) argue against significant metamorphic growth or overgrowths. The wide range of zircon ages and the similarity of those ages with known igneous episodes in the Green Mountain massif and elsewhere in the Grenville Province are inconsistent with thermal resetting. Also of significance is that the zircons were collected only meters away from the contact with the 1.42 Ga tonalite. If thermal resetting occurred or overgrowths formed, it would be reasonable to expect a cluster of about 1.42 Ga ages rather than the wide assortment of younger ages found.

DISCUSSION

Dating single detrital zircons is a powerful method for constraining the maximum age of metasedimentary rocks. Our data show that the Cavendish Formation is certainly younger than about 940 Ma and therefore that the 1.42 Ga Felchville Gneiss could not have intruded it. The contact between the tonalite and the Cavendish Formation in Cavendish gorge is probably a fault and not an unconformity as shown by Doll and others (1961). The strong deformational fabric in rocks near the contact and the truncation of the metasedimentary units are both consistent with a fault contact.

Some problems remain with the assignment of rocks by Doll and others (1961) to the Cavendish Formation. They included in the Cavendish Formation a group of rocks in the northern part of the Green Mountain massif near Wilcox Hill in the Rutland, Vermont, 15′ quadrangle (fig. 1). These rocks were mapped by Brace (1953) as the Wilcox Formation and are lithologically unlike the rest of the Cavendish Formation. Karabinos (1987) interpreted this area as containing thrust sheets composed of both the Mount Holly Complex and Tyson Formation. Locally, other exposures of metasedimentary rocks in the Green Mountain massif and Chester dome that were designated as Cavendish Formation by Doll and others (1961) are almost certainly part of the Mount Holly Complex. For example, rocks on Bear Hill (fig. 1) 2 km south of Grafton, Vermont, are shown by Doll and others (1961) as a thin layer of the Readsboro Member surrounded by Bull Hill Gneiss. This quartz-rich schist is unlike the rest of the Readsboro Member but very similar to a unit in the Mount Holly Complex that contains garnet and sillimanite and records high-grade Grenvillian metamorphism. However, problems with rocks assigned to the Cavendish Formation, such as these two examples, are rare; most of the rocks assigned by Doll and others (1961) to the metasedimentary units of the Cavendish Formation can be reasonably correlated with either the Tyson or Hoosac Formations.

The name Cavendish Schist was not well defined by Richardson (1929). Both the Cavendish Schist and Gassetts Schist of Richardson (1929) became part of the Readsboro

Member of the Cavendish Formation in the compilation of Doll and others (1961), who also included calcsilicate rocks, marbles, quartzites, and the Bull Hill Gneiss in the formation. Doll and others (1961) specified that the Cavendish Formation included rocks whose structural and stratigraphic significance were unclear at the time of their compilation. Ratcliffe and others (1996, 1997) used the name Cavendish Formation only for metasedimentary rocks in the Cavendish Formation of Doll and others (1961). Further, they excluded from this formation many exposures of these rocks in the Wilmington dome and Jamaica, Vermont, areas (fig. 1). The name Cavendish Formation has outlived its usefulness. It has meant quite different things to different geologists, and perpetuation of the term can only lead to further confusion.

We conclude that the metasedimentary rocks we studied from Cavendish gorge cannot be part of the Mount Holly Complex and are best correlated with the Tyson and Hoosac Formations.

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