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U-Pb ZIRCON AGE OF METAFELSITE FROM THE PINNEY HOLLOW FORMATION: IMPLICATIONS FOR THE DEVELOPMENT OF THE VERMONT APPALACHIANS

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ABSTRACT. The Pinney Hollow Formation of central Vermont is part of a rift-clastic to drift-stage sequence of cover rocks deposited on the Laurentian margin during the development of the Iapetan passive margin in Late Proterozoic to Cambrian time. Conventional U-Pb zircon data indicate an age of 571 ± 5 Ma for a metafelsite from the Pinney Hollow Formation. Geochemical data indicate that the protolith for the metafelsite, now a quartz-albite gneiss or granofels, was rhyolite from a source that was transitional between a within-plate granite and ocean-ridge granite setting and probably came through partially distended continental crust. The transitional setting is consistent with previous data from metabasalts in the Pinney Hollow Formation and supports the idea that the source magma came through continental crust on the rifted margin of the Laurentian craton. The 571 ± 5 Ma age provides the first geochronologic age from the rift-clastic cover sequence in New England and establishes a Late Proterozoic age for the Pinney Hollow Formation. The Late Proterozoic age of the Pinney Hollow confirms the presence of a significant mapped thrust fault between the autochthonous and para-autochthonous rocks of the cover sequence. These findings support the interpretation that the Taconic root zone is located in the hinterland of the Vermont Appalachians on the eastern side of the Green Mountain massif.

INTRODUCTION

The Pinney Hollow Formation of central Vermont is part of a para-autochthonous eugeoclinal rift-clastic to drift-stage sequence deposited on the Laurentian margin during the development of the Iapetan passive margin in Late Proterozoic to Cambrian time. The Pinney Hollow Formation consists of metamorphosed pelitic and psammitic sedimentary rocks and lesser amounts of predominantly mafic volcanic rocks exposed east of Middle Proterozoic basement gneiss and schist in the Green Mountains of Vermont (fig. 1). Prior to plate tectonic models, the cover rocks were considered to be an eastward-dipping and -younging homoclinal sequence of coherent stratigraphy (Doll and others, 1961). In the past 15 years, many faults have been identified in the "eastern cover sequence" throughout Vermont. As a result, the Pinney Hollow Formation is now considered part of a fault-bounded lithotectonic belt with its own internal stratigraphy (Walsh and Ratcliffe, 1994a, b; Walsh and Falta, 1996a, b, and in press; and Ratcliffe, Walsh, and Aleinikoff, 1997). Similarities between the metasedimentary rocks of the eastern cover sequence and metasedimentary rocks in the lower parts of the Taconic allochthons have long been recognized. These lithic similarities led early workers to suggest that the source of the Taconic slices was in the eastern cover sequence on the east side of the Green Mountain massif in Vermont and the Berkshire massif in Massachusetts (Keith, 1932; Prindle and Knopf, 1932; Osberg, 1952). More recently, Stanley and Ratcliffe (1985) postulated that the Taconic root zone was exposed at the western edge of the Pinney Hollow, Underhill, and Hazens Notch Formations at the latitude of the northern end of the Taconic allochthons. Stanley and Ratcliffe (1985) assigned these three formations to lithotectonic belts called the Pinney Hollow and Underhill slices and interpreted the western limit of these slices as the root zone for the Taconic allochthons. The geochemistry of the mafic volcanic rocks in the eastern cover sequence, from alkalic to transitional within-plate basalts in the west to MORB-like basalts in the east, has been linked to the relative original geometry of the ancient margin. In this model, west to east

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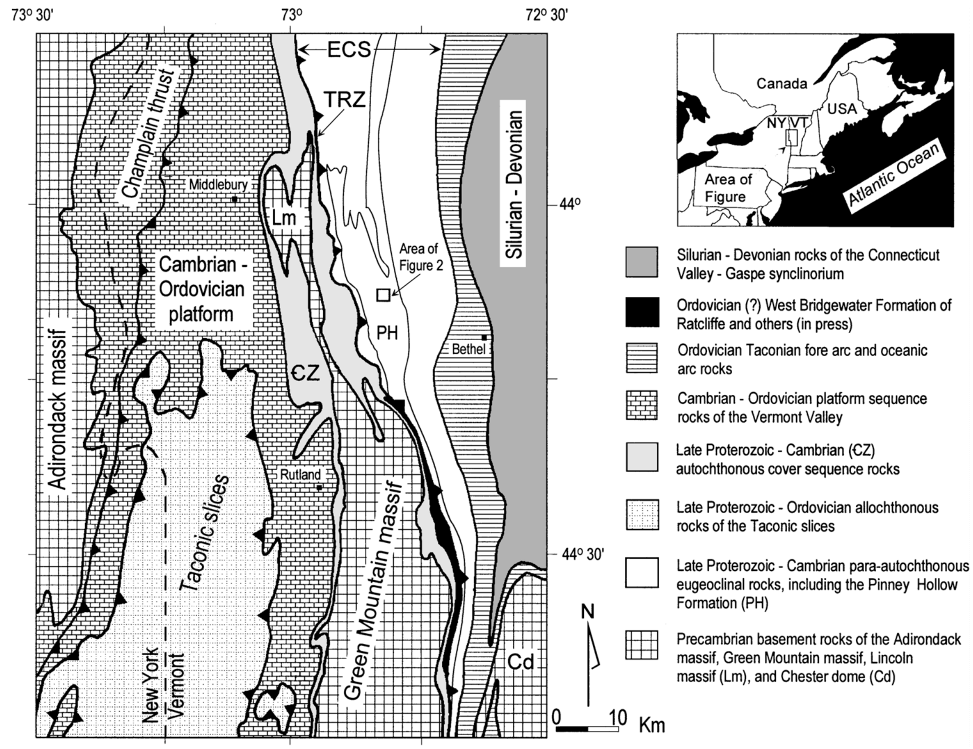

Fig. 1. Generalized tectonic map of west central Vermont and adjacent eastern New York. Geology modified from Stanley and Ratcliffe (1985). TRZ = Taconic root zone of Stanley and Ratcliffe (1985), ECS = eastern cover sequence.

progressive rifting led to highly distended continental crust and subsequent development of oceanic crust during the development of the Iapetan passive margin (Coish and others, 1985, 1986, 1991).

All tectonic interpretations for the evolution of the eastern cover sequence to date have relied on regional correlations to provide age constraints on the rocks. Precise ages for the rocks have been elusive due to a lack of fossils, a lack of datable volcanic rocks, and the abundance of faults that complicate the stratigraphy and prohibit direct correlation with rocks of more certain age. In the west, mafic dikes intrude the Middle Proterozoic basement rocks and cut their Grenvillian tectonic fabric but in turn are cut by an unconformity at the base of the autochthonous cover sequence (DelloRusso and Stanley, 1986). The dikes are interpreted as Late Proterozoic feeders to rift-related metabasalts (DelloRusso and Stanley, 1986; Coish and others, 1991). On the western side of the Green Mountain anticlinorium, the Cambrian to Ordovician platform sequence conformably overlies the autochthonous cover sequence. Near the base of the platform sequence in Bennington, Vermont, the Cheshire Quartzite contains *Olenellus, Nothosoe,* and *Hyolithes* fossils (Walcott, 1888), thus providing a minimum Lower Cambrian age for the autochthonous cover sequence and the correlative rocks of the eastern cover sequence. An age of 554 +4/−2 Ma from comenditic metafelsites interbedded with metabasalt near the top the Tibbit Hill Formation in southern Québec (Kumarapeli and others, 1989) provides the only absolute age for correlative rocks in the autochthonous cover sequence.

Here we present data on the geologic setting, age, and chemistry of a recently mapped metafelsite from the Pinney Hollow Formation and discuss the significance of these findings to the development of the Vermont Appalachians.

GEOLOGIC SETTING

The Pinney Hollow Formation consists largely of silvery green, chlorite, quartz, sericite phyllite, and fine-grained schist interlayered with lesser amounts of mappable gray-green albite-studded chlorite, quartz, muscovite schist; chloritoid, chlorite, quartz, sericite schist; quartzite; feldspathic quartz schist; biotite, chlorite, muscovite, plagioclase, quartz granofels or metawacke; carbonaceous to graphitic schist; green calcite schist; calcite marble; metabasalt or greenstone; and metafelsite. The metafelsite crops out entirely within a large greenstone unit on the western slopes of Austin Hill in the town of Rochester, Vermont (fig. 2) (Walsh and Falta, 1996a, b, and in press). Along the margins, the metafelsite is interlayered on a centimeter scale with greenstone and, to a lesser extent, with the silvery green schist.

The metafelsite is a white to pale-green, well laminated to massive, medium- to fine-grained, light-pink to rusty gray-weathering, calcite, muscovite, quartz, albite gneiss

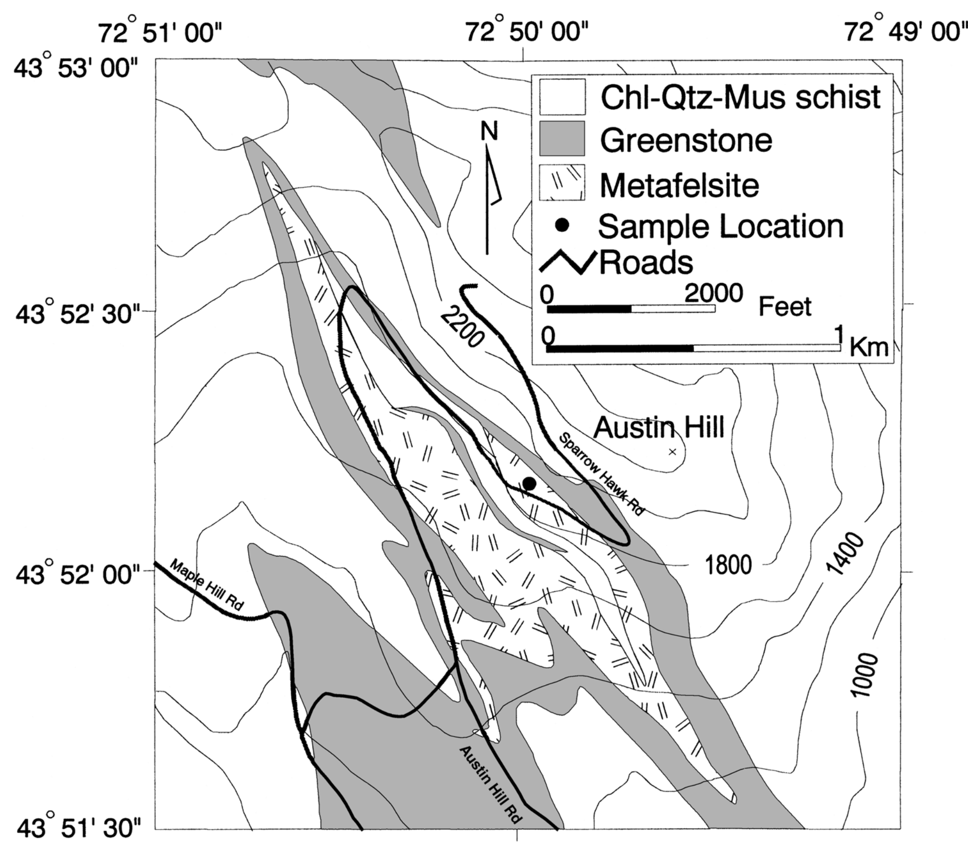

Fig. 2. Generalized geologic map of the Austin Hill area in Rochester, Vermont showing the location of samples RO-314A and RO-314B. Geology south of 43° 52′ 30″ from Walsh and Falta (1996a, b, and in press). Contours in feet from 7.5-minute Rochester, Vermont U.S. Geological Survey topographic quadrangle (1970 edition), interval is 200 feet (61 meters).

to granofels with accessory epidote and opaque minerals. The rock consists mostly (70-80 percent) of 0.05- to 0.20-mm grains of quartz and albite, and contains variable amounts of muscovite that define the foliation. In places, the metafelsite is interlayered with coarse-grained, silvery white, quartz, muscovite schist suggesting locally significant hydration during greenschist facies metamorphism. Segregated layers of quartz and plagioclase, 0.2- to 1.0-mm thick, are bounded by muscovite where the rock is laminated. The metafelsite contains <5 percent rectangular to semi-rectangular porphyroclasts of plagioclase, as much as 0.4 mm wide and 1.5 mm long, interpreted as fragmented phenocrysts (fig. 3). The composition, delicate interlayering with the greenstone, presence of phenocrysts, and occurrence within a largely pelitic sequence suggest that the metafelsite is a metamorphosed, water-lain, felsic tuff within a largely mafic volcanic deposit. The greenstones are typically fine grained, well laminated, and lack any flow structures or textures and are probably mafic tuffs and volcaniclastic rocks.

The metafelsite and the surrounding rocks are highly deformed, and the rock fabric is dominated by two generations of sub-parallel northwest-striking and northeast-dipping foliation that are products of the Ordovician Taconian orogeny (Taconian S_1 and S_2). The second-generation foliation is locally mylonitic and is characterized by east-southeast trending, down-dip mineral lineations and fold axes, and sheath folds. Third and fourth generations of deformation produced steeply dipping cleavage and associated open to tight folds with shallow north- and south-plunging fold axes, and northeast-striking and northwest-dipping kink bands and spaced cleavage during the Devonian Acadian orogeny (Acadian S_3 and S_4, respectively). Paleozoic metamorphism in the area reached greenschist-facies conditions during the Taconian (biotite zone) and Acadian orogenies (chlorite zone).

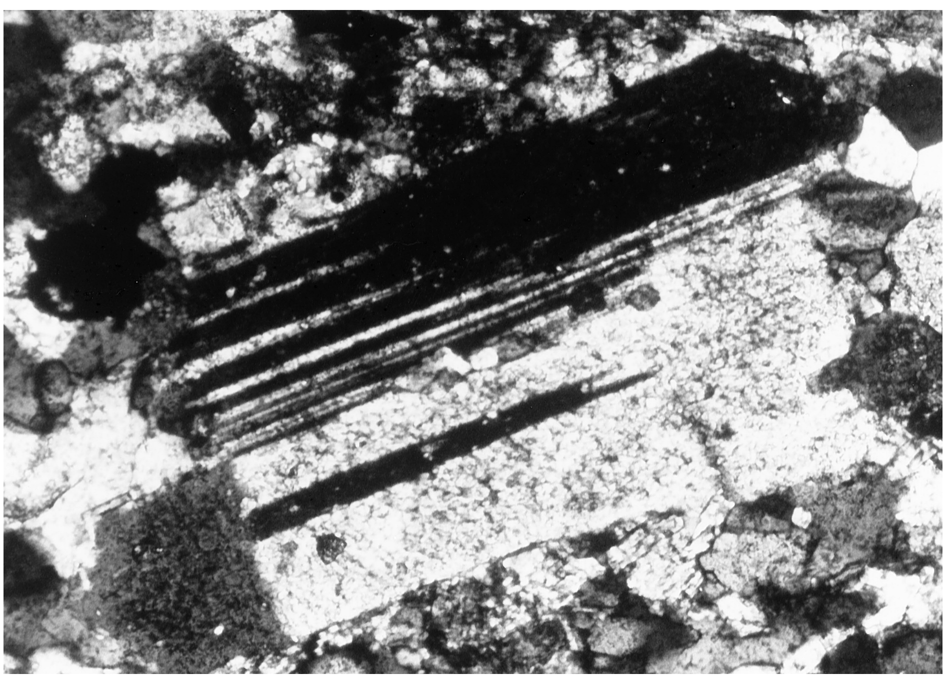

Fig. 3. Photomicrograph of angular plagioclase porphyroclast from the metafelsite in the Pinney Hollow Formation. This and similar porphyroclasts are interpreted as fragmented phenocrysts. Photomicrograph of sample RO-314B through 10X objective in polarized light, field of view is 0.75×0.5 mm.

The Pinney Hollow Formation is fault-bounded to the east by the Cambrian(?) Ottauquechee Formation (Walsh and Falta, 1996a, b, and in press; Walsh and Ratcliffe, 1994a, b; Ratcliffe, Walsh, and Aleinikoff, 1997; Walsh and Ratcliffe, 1998). The formational boundary is interpreted largely as a syn-metamorphic Taconian-aged fault. Locally, however, the boundary pre-dates the peak of Taconian metamorphism and is characterized by upper and lower plate truncations suggesting that it is a pre-metamorphic thrust fault. Subsequent faulting during peak Taconian metamorphic conditions transposed most of the older pre-metamorphic fault contacts. Still younger Acadian deformation produced locally significant fault zones that further complicate the tectonic history of the Pinney Hollow–Ottauquechee contact. The Ottauquechee Formation contains deep-water slope-rise metasedimentary rocks with serpentinized ultramafic bodies as either fault slivers (Stanley and Roy, 1982; Stanley and others, 1984) or olistoliths (Walsh and Ratcliffe, 1994a). The western boundary of the Pinney Hollow Formation is a Taconian fault south of the northern latitude of the Green Mountain massif (Walsh and Ratcliffe, 1994a, b; Ratcliffe, Walsh, and Aleinikoff, 1997; Walsh and Ratcliffe, 1998). North of the Green Mountain massif and south of the Lincoln massif, however, the western boundary of the Pinney Hollow is a depositional contact with the informal Fayston formation and is only locally transposed by Taconian faults (Walsh and Falta, 1996a, b, and in press; Walsh and Ratcliffe, 1998). The Fayston formation consists largely of gray-green albite-studded schist with minor carbonaceous albite schist, quartzite, silvery green schist (like the Pinney Hollow), biotite metawacke and granofels, and greenstone (Walsh, 1992; Walsh and Falta, 1996a, b, and in press). North of the Lincoln massif, the western formational boundary is interpreted as a syn-metamorphic or pre-metamorphic Taconian fault against the informal Granville formation (Walsh, 1992). The Granville formation consists largely of carbonaceous albite schist interlayered with black and white quartzite (Walsh, 1992).

U-Pb GEOCHRONOLOGY

Zircons from the metafelsite are euhedral with length-to-width ratios of about 3 to 6, and most contain sharp pyramidal terminations. Nearly all grains have mottled faces and are extensively cracked (fig. 4). The zircons appear to be from a single, unimodal population, and no detrital zircon component was recognized. Pb and U were extracted from zircon following procedures described in Aleinikoff and others (1996). Isotopic ratios were measured on a VG 54E mass spectrometer with single Faraday cup and Daly multiplier collectors. Raw data were reduced and plotted using computer programs of Ludwig (1991a, b).

Isotopic data from seven fractions (table 1) are very similar; Pb/U ages range from 554 to 570 Ma, and ^{207}Pb/^{206}Pb ages range from 567 to 574 Ma. Despite the cracked nature of most of the zircons, the isotopic data are a maximum of about 3 percent discordant. A best-fit discordia through all the data points yields intercept ages of 134 $\pm$ 230 and 573 $\pm$ 12 Ma (fig. 5). Because of limited spread in the data, a better estimate of the age is the weighted average of the ^{207}Pb/^{206}Pb ages, 569.6 $\pm$ 1.2 Ma (fig. 5). This calculation assumes that only modern Pb-loss has affected the isotopic systematics. If the uncertainties in the decay constants are included in the calculation, the upper intercept age of the zircon from the Pinney Hollow metafelsite is about 571 $\pm$ 5 Ma.

From the zircon population and morphology, the association with metabasalt or greenstone, and the relict phenocrystic texture, we believe the metafelsite represents a primary volcanic rock (a water-lain tuff) and not a reworked or recycled volcaniclastic deposit. Volcanic textures are long since obliterated by deformation and metamorphism, so we can not unequivocally state that the metafelsite was a primary volcanic rock. The

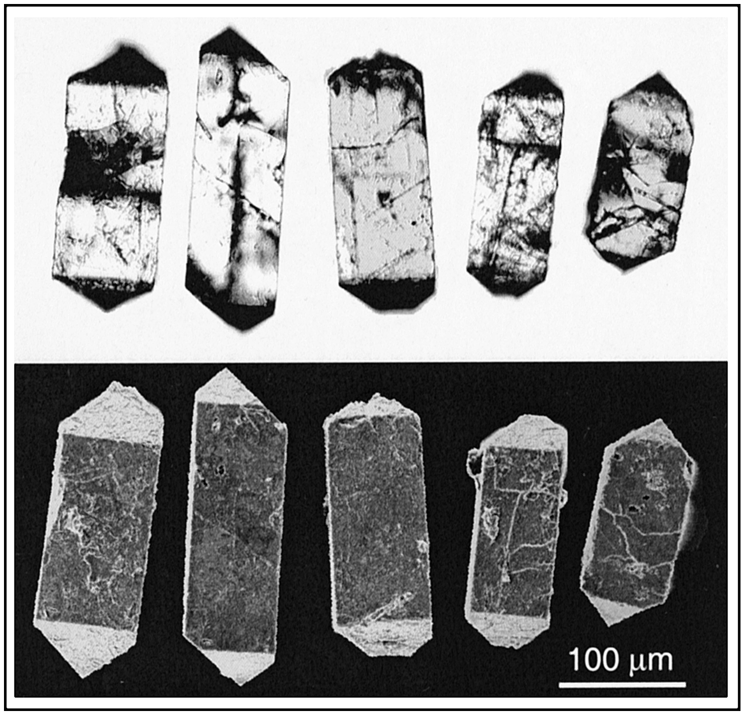

Fig. 4. Photomicrographs of five zircons from the metafelsite in the Pinney Hollow Formation. The transmitted light image on top and the secondary electron SEM image on the bottom are in the same orientation.

TABLE 1

Uranium-lead geochronology of zircon from metafelsite, Pinney Hollow Formation, Vermont

Fraction*	Wt. (mg.)	Concentration (ppm) U	Concentration (ppm) Pb	Pb Composition** 206Pb/204Pb	Pb Composition** 206Pb/207Pb	Pb Composition** 206Pb/208Pb	Ratios (% error)*** 206Pb/238U	Ratios (% error)*** 207Pb/235U	Ratios (% error)*** 207Pb/206Pb	Ages (Ma)**** 206Pb/238U	Ages (Ma)**** 207Pb/235U	Ages (Ma)**** 207Pb/206Pb
	sample RO-314B											
(−100 + 150)1	.011	248.4	27.48	716.54	12.594	3.3537	.7411 (.70)	.0909 (.52)	.0591 (.45)	561	563	572
(−100 + 150)2	.027	299.0	32.17	1035.5	13.677	3.4932	.7355 (.31)	.0903 (.27)	.0591 (.14)	557	560	570
(−100 + 150)3	.024	308.1	32.90	3302.2	15.729	3.6624	.7528 (.55)	.0923 (.37)	.0592 (.38)	569	570	574
(−100 + 150)4	.058	295.8	30.62	2716.6	15.528	3.7359	.7301 (.30)	.0897 (.29)	.0591 (.07)	554	557	569
(−100 + 150)5	.023	256.3	27.73	1116.5	13.885	3.4189	.7368 (.48)	.0906 (.45)	.0590 (.17)	559	561	567
(−100 + 150)6	.154	68.71	7.477	884.96	13.238	3.4171	.7373 (.54)	.0904 (.51)	.0591 (.17)	558	561	572
(−100 + 150)7	.018	216.9	24.47	605.2	12.041	3.1322	.7374 (.60)	.0906 (.52)	.0590 (.29)	559	561	569

*All zircons are euhedral; most contain numerous cracks.

**Pb isotopic composition ratios corrected for 0.14 ± .05 percent/a.m.u. mass fractionation and blank Pb (15–20 ± 25 percent pg) of composition 1:18.8:15.7:38.5.

***2σ errors.

****Ages corrected for common lead using the appropriate values from Stacey and Kramers (1975) for 570 Ma.

Constants: 235λ = 9.8485 E-10/yr; 238λ = 1.55125E-10/yr; 238U/235U = 137.88 (Steiger and Jäger, 1977).

evidence does suggest, however, that mafic and felsic rocks were deposited contemporaneously in a largely pelitic sequence without significant reworking or recycling. The age of the zircon, therefore, is interpreted as the age of volcanism and deposition of the metafelsite.

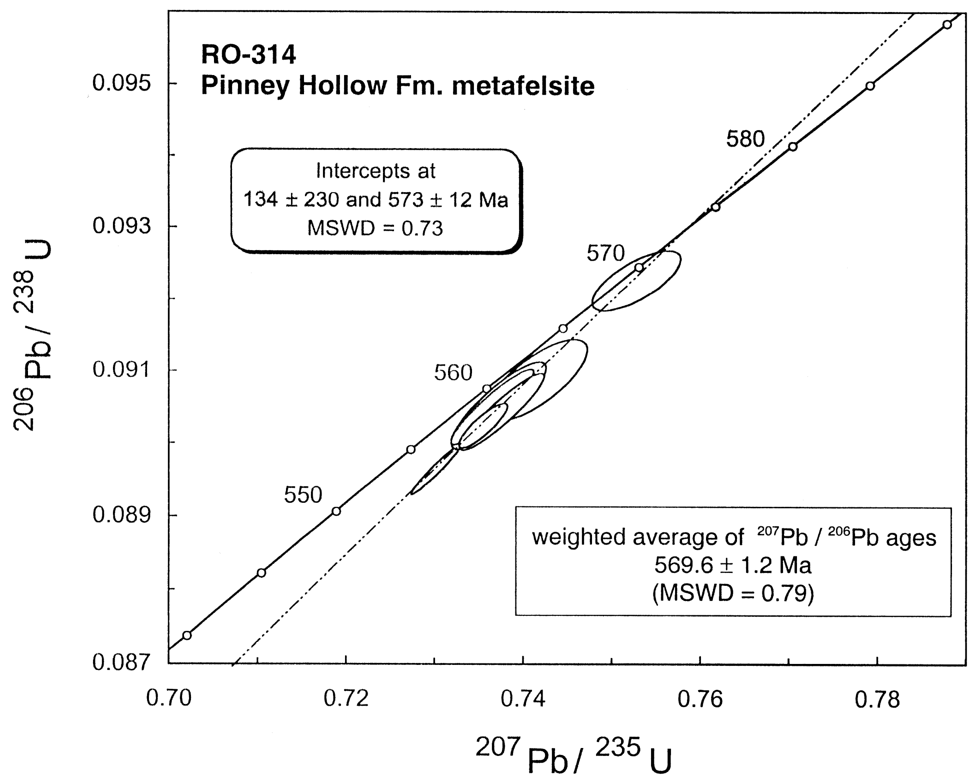

Fig. 5. Concordia plot of data from sample RO-314B from metafelsite of the Pinney Hollow Formation. See text for discussion of data points used for regression.

GEOCHEMISTRY

Whole-rock geochemistry for major and trace elements was completed for two unweathered samples of the metafelsite (table 2). Due to the degree of deformation and metamorphism exhibited in the rock, a more micaceous sample (RO-314A) was collected for comparison with the more typical quartzofeldspathic gneiss (RO-314B, the dated rock). Considerable variation in the mobile major oxides SiO_2, MgO, CaO, Na_2O, and K_2O is undoubtedly due to metamorphism, but the rock can be generally classified as subalkaline.

Despite the significant differences in major-element chemistry between the two samples, the trace-element chemistry is quite consistent and indicates that the protolith of the metafelsite was rhyolite (fig. 6). The classification scheme of Winchester and Floyd (1977), shown in figure 6, is the most reliable method for categorizing altered or metamorphosed felsic volcanic rocks, because it is based on supposedly immobile trace elements. On the Ta versus Yb diagram of Pearce and others (1984), the metafelsite plots in the field of within plate granite (WPG) (fig. 7). The rocks are enriched in Th, Ta, and Ce relative to ocean ridge granite (ORG), show relative enrichment of Ce and Sm relative to adjacent elements, but show no negative Ba anomalies (fig. 6, after Pearce and others, 1984). Values from Hf to Yb are relatively flat and close to normalized ORG. Generally, the spider diagrams (fig. 8) show patterns typical of rocks from a crust-dominated environment in attenuated continental lithosphere (Pearce and others, 1984). For comparison, the comenditic metafelsites from the Tibbit Hill Formation (Kumar-

TABLE 2

Major and trace element geochemistry of metafelsite from the Pinney Hollow Formation

	RO-314A	RO-314B		RO-314A	RO-314B
Major elements (wt %)			Trace elements (ppm) (continued)		
SiO_2	65.50	74.28	Zr	369.0	369.0
Al_2O_3	11.69	11.58	Nb*	24	26
Fe_2O_3	2.31	2.43	Sb	0.827	0.129
MgO	1.20	0.47	Cs	0.61	0.35
CaO	6.13	2.10	Ba	633.0	476.0
Na_2O	2.56	4.41	La	58.50	50.90
K_2O	3.82	1.81	Ce	126.0	123.0
TiO_2	0.15	0.15	Nd	68.20	60.40
P_2O_5	<0.05	<0.05	Sm	15.700	13.600
MnO	0.06	0.04	Eu	2.200	1.950
LOI	6.01	2.37	Gd	15.20	12.50
Total	99.47	99.68	Tb	2.38	1.99
Trace elements (ppm)			Ho	3.2	2.7
Sc	3.850	3.610	Tm	1.38	1.20
Cr	1.4	0.2	Yb	8.42	7.38
Co	0.15	0.22	Lu	1.200	1.070
Ni	5.7	15.0	Hf	11.00	10.90
Zn	86.5	75.3	Ta	2.560	2.540
As	20.1	4.31	W	0.49	0.64
Rb	84.100	42.100	Au†	0.4	0.5
Sr	88.7	58.6	Th	8.680	8.300
Y*	83	68	U	0.96	1.27

Notes: Major element analyses by WDXRF of lithium tetraborate fused beads, analyst David F. Siems, United States Geological Survey, Denver, Colorado; detection limits = SiO_2(.10 percent), Al_2O_3(.10 percent), Fe_2O_3 (.04 percent), MgO(.10 percent), CaO(.02 percent), Na_2O(.15 percent), K_2O(.02 percent), TiO_2(.02 percent), P_2O_5(.05 percent). MnO(.01 percent), precision = 1–2 percent RSD. Trace element analyses by INAA; analyst James R. Budahn, USGS, Denver, Colorado, detection limits and precision estimates reported in Baedecker and McKown (1987).

†Au measured in ppb.

*Nb and Y analyses by EDXRF of pressed powder pellets, analyst XRAL Laboratories, Don Mills, Ontario, Canada; detection limit = 2 ppm, precision = ±2%. Sample location: Roadcut on Sparrow Hawk Road on the southwestern slope of Austin Hill, Rochester, Vermont, lat. 43°52′08″ N, long. 72°52′00″ W, Rochester, Vermont 7.5-minute quadrangle. Sample descriptions: RO-314A–white to pale-green, calcite, quartz, muscovite, plagioclase gneiss; RO-314B–white to pale-green, locally pinkish rusty red weathering, calcite, muscovite, quartz, plagioclase gneiss to granofels.

apeli and others, 1989) show less of an ORG trend from Hf to Yb, suggesting that perhaps the crust was less attenuated beneath the Tibbit Hill (fig. 8). The REE patterns for the metafelsite show light REE enrichment and a pronounced negative Eu anomaly (fig. 9).

TECTONIC IMPLICATIONS

The new data provide the first geochronologic age from the eastern cover sequence in Vermont. With the age of the Proterozoic-Cambrian boundary estimated at 544 Ma (Bowring and others, 1993), the 571 ± 5 Ma age from the metafelsite establishes a Late Proterozoic age for the Pinney Hollow Formation. The age supports the interpretation that the Pinney Hollow is part of the pre-shelf rift-clastic sequence and, combined with recent paleontologic evidence (Ratcliffe, Harris, and Walsh, in press; see discussion below), provides the first corroborative evidence of major thrust faults within the eastern cover sequence.

The 571 ± 5 Ma age agrees with other Late Proterozoic ages from rift-clastic volcanic rocks in the Appalachians. The most similar ages come from the southern Appalachians and include metarhyolite from the Catoctin Formation at 564 ± 9 Ma and a felsic dike at 572 ± 5 Ma which intrudes Middle Proterozoic basement (Aleinikoff and others, 1995). According to Aleinikoff and others (1995), these ages are associated with

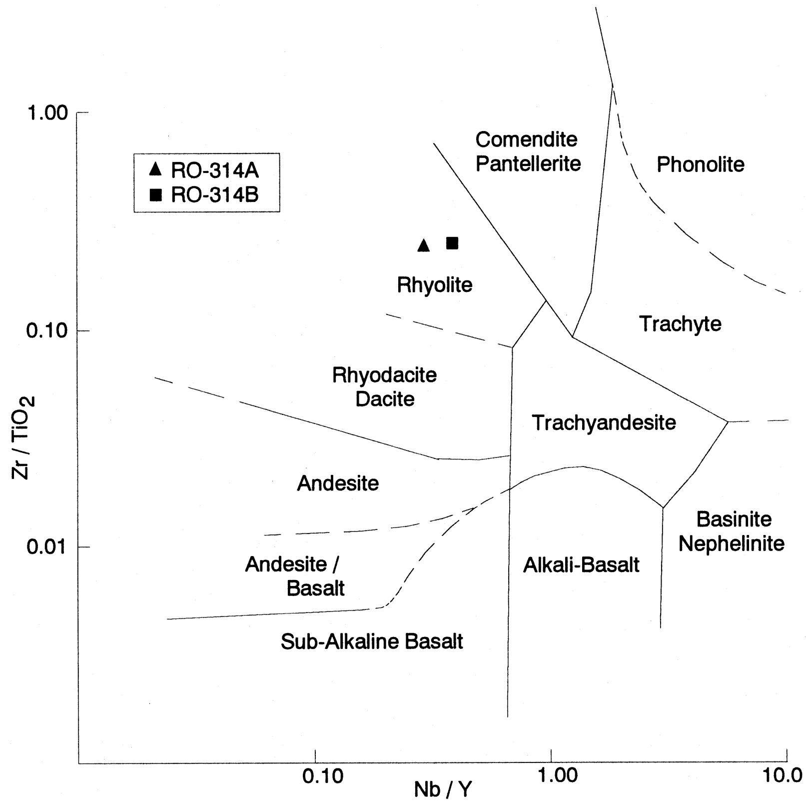

Fig. 6. Zr/TiO_2 versus Nb/Y classification diagram for common volcanic rocks of Winchester and Floyd (1977). The Pinney Hollow metafelsite samples (RO-314A and RO-314B) plot as rhyolite.

the second phase of continental rifting which led to the opening of the Iapetus Ocean. In southern Québec, Kumarapeli and others (1989) reported a 554 +4/−2 Ma age from comenditic metafelsite near the top of the Tibbit Hill Formation.

Prior to this study, the metafelsite from the Tibbit Hill was the only reported occurrence of Late Proterozoic felsic extrusive rocks in the eugeoclinal sequence in the northern Appalachians south of Newfoundland. The scarcity of felsic volcanic rocks in the north contrasts sharply with the large volume in the southern Appalachians. In the South Mountain area of Pennsylvania the Catoctin Formation contains more metafelsic rock than metabasalt (Fauth, 1978). Similar ages also occur in intrusive rocks from the Manhattan Prong. Rankin and others (1997) reported U-Pb zircon ages of 563 ± 3 Ma for the Yonkers Gneiss of Long (1969) and 562 ± 6 Ma for the Pound Ridge Granite Gneiss of Mose and Hayes (1975). Rift-related felsic intrusive rocks are absent from the eugeoclinal part of the Vermont and Québec Appalachians, but an age of 602 ± 10 Ma has been reported from the Round Pond granite in Newfoundland (Williams and others, 1985).

In southern Québec (Kumarapeli and others, 1989), the metafelsic rocks occur near the top of a thick metavolcanic section and are overlain by a sequence dominated by coarse clastic rocks from a shallow water environment (Colpron and others, 1987). In contrast, the Pinney Hollow metavolcanic rocks occur within a deep-water pelagic sequence. The fine-grained schist and phyllite in the Pinney Hollow contain small

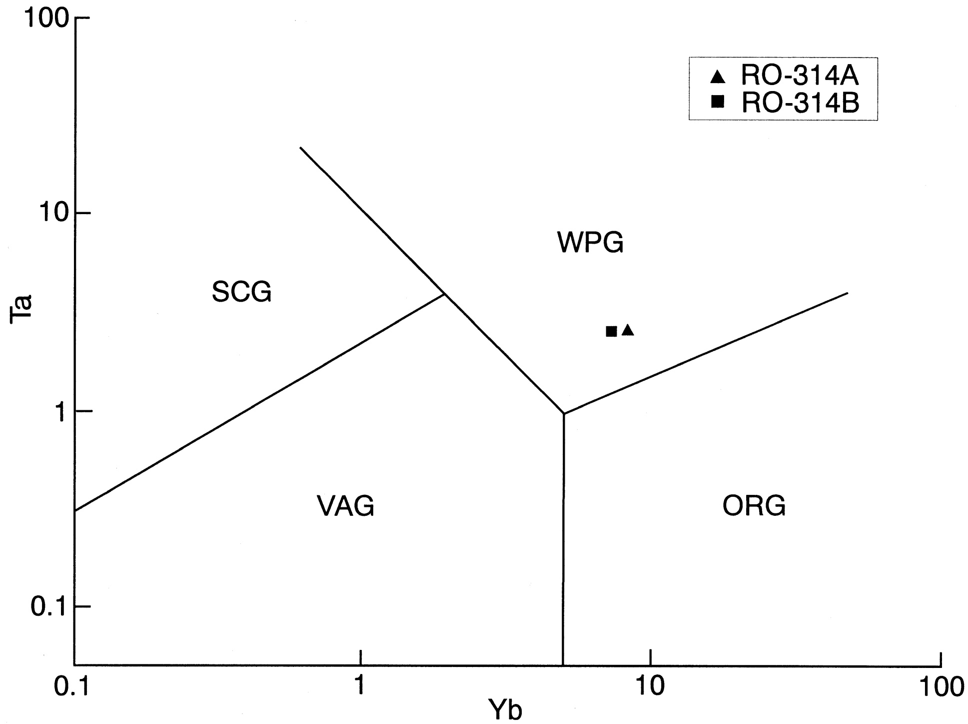

Fig. 7. Ta-Yb tectonic discrimination diagram for granitic rocks of Pearce and others (1984) showing the Pinney Hollow metafelsite samples (RO-314A and RO-314B) are from a within plate granite (WPG) setting. SCG = syn-collision granites, VAG = volcanic arc granites, ORG = ocean ridge granites. Units are in ppm.

amounts of interbedded blue-quartz pebble metawacke and quartz-rich sandy schist but generally lack proximal metaclastic rocks. The stratigraphic and geochronologic data suggest, therefore, that the basin was already well developed when the 571 Ma metafelsite was deposited. Clearly the 554 Ma age for the Tibbit Hill at the proposed Sutton Mountain rift-rift-rift triple junction (Rankin, 1976; Kumarapeli and others, 1981, 1989) does not represent the first pulse of volcanic activity during the initial opening of the Iapetan basin in the Vermont and Québec Appalachians.

Coish and others (1985, 1986, 1991) and Coish (1989) presented a model of progressively distended continental crust through time on the basis of the change in geochemistry of metabasalts across the Appalachian orogen in Vermont and New York. In this model, older western basalts with enriched Ti and light REE erupted from an enriched mantle source (their zones 1 and 2), and younger eastern basalts with depleted Ti and light REE erupted from a depleted MORB asthenosphere (their zone 4). Metabasalts within the Pinney Hollow Formation, assigned to zone 3 (Coish, 1989; Coish and others, 1991), have compositions that range between the two endmembers and reflect a source that includes both enriched and depleted mantle. The geochemistry of the metafelsite agrees with the transitional geochemistry of the metabasalts for zone 3, but the age questions the validity of this model. According to Coish and others (1991) the Tibbit Hill rocks of zone 2 erupted at approximately 554 Ma (Kumarapeli and others, 1989) and were followed by the eruption of zone 3 Pinney Hollow rocks. The new 571 Ma age questions the simple model of progressive geochemical change with time, but the geochemistry does allow for eruption of the metafelsite through partially distended

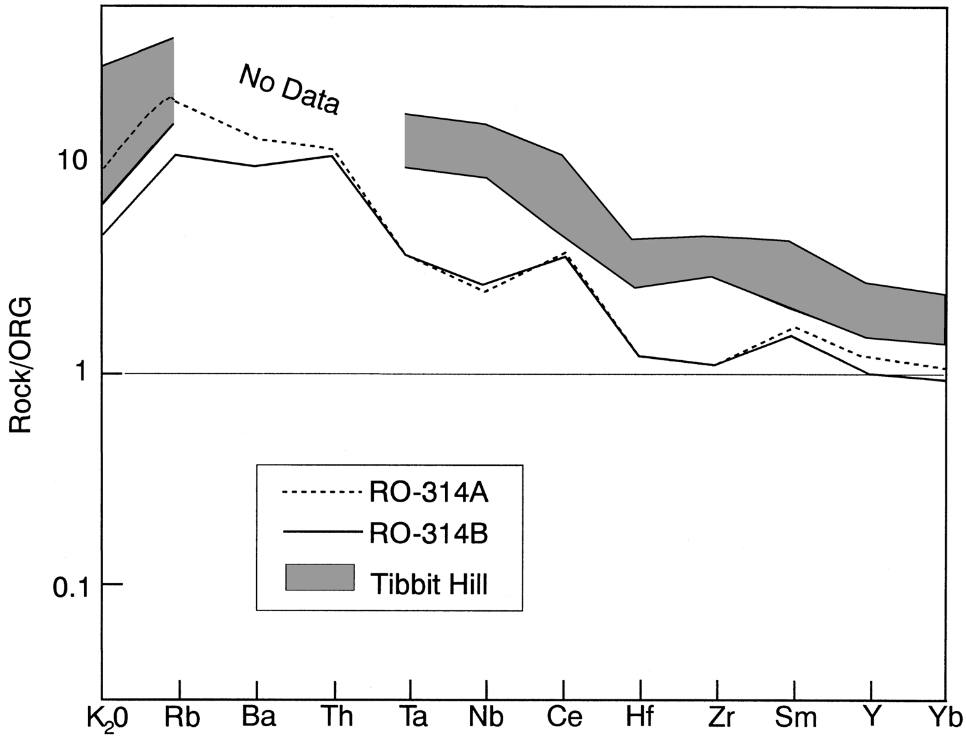

Fig. 8. Spider diagram normalized to ocean ridge granite (ORG) after Pearce and others (1984) for Pinney Hollow metafelsite samples RO-314A and RO-314B. Plots are typical of a Pearce and others (1984) third type within plate granite from attenuated continental lithosphere. Units are in ppm and wt percent (K_2O). Tibbit Hill metafelsite data are from Kumarapeli and others (1989).

continental crust. Because the metafelsite in the Pinney Hollow is transported volcanic rock, the volcanic center was not in the Pinney Hollow basin. Thus, the partially distended continental crust through which the Pinney Hollow metafelsite erupted must have been outside the basin on the rifted margin of the craton, prior to the eruption of the metafelsite at the top of the Tibbit Hill. In general, the model of progressive chemical change through time may still be valid if taken in a regional context. Considering the chemical overlap between zones 2 and 3 and the lack of ages from zones 1 and 4, it is difficult to establish conclusively the complete temporal span of rifting with only the 554 and 571 Ma ages. The +54 mGal gravity anomaly associated with the Tibbit Hill suggests that it is one of the largest masses of rift volcanic rock in the Appalachians (Kumarapeli, Goodacre, and Thomas, 1981). It is still possible that rocks older than 554 Ma exist at the unexposed depths of the Tibbit Hill, and that rocks younger than 571 Ma exist in the Pinney Hollow. It is clear, however, that despite the remaining questions, the Pinney Hollow metafelsite was deposited during a time when rift volcanism was widespread throughout the central to northern Appalachians.

Many thrust faults have been identified in the eastern cover sequence through detailed mapping of lithostratigraphy, upper and lower plate truncations, and, in the case of syn- and post-metamorphic faults, tectonic fabrics (Stanley and others, 1987; Ratcliffe, Armstrong, and Tracy, 1992; Ratcliffe, Walsh, and Aleinikoff, 1997). Until now, none of the faults could be corroborated with paleontologic and geochronologic evidence. The recent discovery of Middle Ordovician conodonts in the West Bridgewater Formation

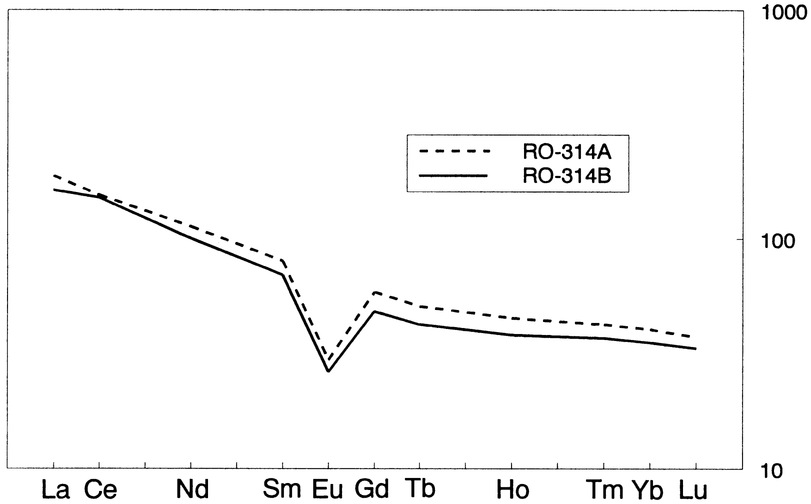

Fig. 9. Chondrite normalized plot of REE for the Pinney Hollow metafelsite samples RO-314A and RO-314B. Note the similarity of the plots despite the significant differences in major element geochemistry.

represents the first report of fossils in the cover sequence east of the Green Mountain massif in Vermont (Ratcliffe, Harris, and Walsh, in press). The West Bridgewater Formation is exposed west of and structurally below the Pinney Hollow Formation at the top of the autochthonous cover sequence (fig. 1). The contact between the two formations has been mapped as an eastward-dipping Taconian thrust fault, the Wood Peak fault, and is characterized by mylonitic fabric with down-dip, east- to southeast-trending lineations (Walsh and Ratcliffe, 1994a; Ratcliffe, Walsh, and Aleinikoff, 1997). Similar tectonic fabric is exhibited along the Hoosac Formation–Rowe Schist contact in northern Massachusetts and southern Vermont (Zen and others, 1983; Ratcliffe and others, 1993; Ratcliffe and Armstrong, in press). The new 571 Ma age supports the mapping and requires a major thrust fault between the Late Proterozoic Pinney Hollow Formation and the Middle Ordovician West Bridgewater Formation of Ratcliffe, Harris, and Walsh (in press). The Wood Peak fault, therefore, must represent a major tectonic boundary between the autochtonous and the para-autochthonous cover sequence rocks. This boundary corresponds to the western limit of the Underhill and Pinney Hollow slices of Stanley and Ratcliffe (1985) and supports their interpretation that the location of the Taconic root zone is in the hinterland of the Vermont Appalachians on the eastern side of the Green Mountain massif.

CONCLUSIONS

1. Geochemical data indicate that the protolith of the metafelsite from the Pinney Hollow Formation of Vermont, now a quartz-albite gneiss or granofels, was a rhyolite from a source that was transitional between a within-plate granite and an ocean-ridge granite setting and probably came through partially distended continental crust.

2. A U-Pb zircon age of 571 ± 5 Ma is the first geochronologic age from the rift-clastic cover sequence in New England and establishes a Late Proterozoic age for the Pinney Hollow Formation.

3. In conjunction with recent paleontologic evidence (Ratcliffe, Harris, and Walsh, in press), the new geochronologic data conclusively validate the presence of a significant mapped thrust fault between the autochthonous and the para-autochthonous cover sequence rocks. These findings support the interpretation that the Taconic root zone is

located in the hinterland of the Vermont Appalachians on the eastern side of the Green Mountain massif.

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