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GEOLOGICAL NOTES

Early Rifting in the Narragansett Basin, Massachusetts–Rhode Island: Evidence from Late Devonian Bimodal Volcanic Rocks

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ABSTRACT

The basal Wamsutta Formation of the Narragansett Basin, Massachusetts–Rhode Island, contains 373 ± 2 Ma rhyolite that is unexpectedly 60 m.yr. older than sedimentary strata containing late Pennsylvanian floras higher in the basin fill. The transitional alkalic geochemistry of the rhyolite and associated basalt signifies Late Devonian rifting predating major basin subsidence. Surface rifting was accompanied by voluminous alkalic intrusions of the 380–370 Ma Scituate Igneous Suite into Neoproterozoic basement west of the basin and by ductile extension along shear zones confined to the pluton and neighboring units. The Maritimes Basin and adjoining areas in Atlantic Canada experienced a similar mid-Paleozoic history.

Introduction

Polyphase Permian deformation and metamorphism are well known in southeastern New England, but the nature and timing of preceding Paleozoic tectonic events are less clear. A major chapter in this history is recorded in sedimentary rocks of the Narragansett Basin stretching northward from coastal Rhode Island into eastern Massachusetts (fig. 1). Strata underlying the Massachusetts portion of this broad lowland comprise, in ascending order, the Pondville Conglomerate, the Wamsutta Formation, the Rhode Island Formation, and the Dighton Conglomerate (nomenclature of Shaler et al. 1899, slightly modified by Emerson 1917). Plant fossils in several of these formations indicate deposition during Westphalian B to Stephanian stages of late Pennsylvanian time (most recent biostratigraphic review in Wagner and Lyons 1997).

Until now, florally derived ages for sedimentary deposition in the Narragansett Basin have also served as the major constraint on tectonic models for southeastern New England during the middle

to late Paleozoic. On this evidence alone, the basin was formed and accumulated its Westphalian B to Stephanian sedimentary fill during the remarkably short interval between approximately 310 and 295 Ma (time scale of Harland et al. 1990). Deposition was closely followed by multiple phases of folding and prograde metamorphism in southern portions of the basin (Mosher 1983; Reck and Mosher 1989). Peak metamorphism is estimated at approximately 280 Ma on the basis of mineral thermochronology in Avalonian basement rocks outside the basin on the west (Wintsch and Sutter 1986; Dallmeyer et al. 1990; Wintsch et al. 1992) and isograds in basin rocks that are truncated by approximately 275 Ma Narragansett Pier Granite (U-Pb zircon age of Zartman and Hermes 1987). Biotite cooling ages indicate retrograde effects as young as 240 Ma (Dallmeyer 1982). These age data portray a skewed tectonic evolution in which tectonothermal events lasting 40–50 m.yr. were imprinted on a basin that took less than 15 m.yr. to form.

U-Pb zircon geochronology presented here for rhyolite in the Wamsutta Formation near the stratigraphic base of the Narragansett Basin was undertaken to provide a radiometric constraint on its early history. Our results demonstrate that the rhyolite is 60 m.yr. older than fossiliferous coal-bearing

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Figure 1. Geologic map of southeastern New England (after Zen 1983 and Hermes et al. 1994) emphasizing Paleozoic features. Ages of pre-Devonian plutons reviewed in Hermes and Zartman (1985), ages of Avalonian basement reviewed in Thompson et al. (1996), and maximum age of the Boston Basin from Thompson and Bowring (2000). CNF = Clinton-Newbury fault; BBF = Bloody Bluff fault; LCF = Lake Char Fault; HVSZ = Hope Valley Shear Zone. Unnamed ductile shear zones from Hamidzadeh (1988). Inset at lower right shows enlarged view of boxed area north of South Attleboro.

strata of the Rhode Island Formation that underlies the majority of the basin. Tectonic activity in this area thus began significantly earlier than previously recognized and took place contemporaneously with Late Devonian alkalic intrusions of the nearby Scituate Igneous Suite (Hermes and Zartman 1985). The new age results suggest strong parallels to the coeval Maritimes Basin of Atlantic Canada, where an early phase of rifting and bimodal volcanism was followed by thick sedimentation including deposition of coal measures (Keppie 1982; St. Peter 1993; Pascucci et al. 2000).

The Wamsutta Formation

The Wamsutta Formation (originally the Wamsutta Group of Shaler et al. 1899) crops out in the north-

western corner of the Narragansett Basin and from there extends northeastward through the axis of the Norfolk Basin (fig. 1). Approximately 300 m of red shales and sandstones interbedded with green or gray conglomerates were deposited mainly in fluvial channel and overbank settings (Mutch 1968). Poorly sorted mudflow horizons are also present. Comparable units in the Norfolk Basin are interpreted as braided stream deposits on wet alluvial fans supplied by upfaulted basement blocks to the north (Cazier 1987). Volcanic rocks are interbedded with red beds near the base of the Wamsutta Formation in the vicinity of South Attleboro, Massachusetts. Volcanic units include four basalt flows (45%–49% SiO_2) up to 6 m thick, two rhyolite flows (74%–75% SiO_2) measuring approximately 3 m and

Table 1. U-Pb Isotopic Data for the Wamsutta Rhyolite, South Attleboro, Massachusetts (Sample DH02-17-98)

Sample fraction ^a	Weight (mg)	U (ppm)	P (ppm)	²⁰⁶ Pb/ ²⁰⁴ Pb ^b	²⁰⁸ Pb/ ²⁰⁶ Pb ^c	²⁰⁶ Pb/ ²³⁸ U ^d	²⁰⁷ Pb/ ²³⁵ U ^d	²⁰⁷ Pb/ ²⁰⁶ Pb ^d	²⁰⁶ Pb/ ²³⁸ U	²⁰⁷ Pb/ ²³⁵ U	²⁰⁷ Pb/ ²⁰⁶ Pb	Discordance (%)
Z1 (3)	.001	1613.7	121.1	2479.39	.407	.05962 (.10)	.4439 (.23)	.05400 (.20)	373.3	373.0	371.1	-.6
Z2 (4)	.001	3705.0	289.2	2988.61	.465	.05930 (.13)	.4420 (.16)	.05406 (.09)	371.4	371.7	373.4	.6
Z3 (4)	.002	857.7	66.9	893.16	.418	.05956 (.25)	.4440 (.28)	.05407 (.12)	372.9	373.1	374.0	.3
Z4 (1)	.002	2833.5	211.5	6716.33	.408	.05925 (.07)	.4421 (.12)	.05411 (.09)	371.1	371.7	375.8	1.3
Z5 (4)	.002	1782.1	129.4	4926.78	.376	.05893 (.07)	.4404 (.11)	.05420 (.08)	369.1	370.5	379.3	2.8

Note. Sample weights are estimated from a video monitor with a gridded screen and are known to within 10%.

^a Number of zircons in each sample fraction given in parentheses.

^b Radiogenic lead.

^c Measured ratio corrected for spike and fractionation only. Mass fractionation correction of 0.15%/amu + 0.004% was applied to all analyses.

^d Corrected for fractionation, spike, blank, and initial common Pb; U blank = 1 pg + 50%; Pb blank = 3.5 pg + 50%. Initial Pb composition is calculated from Stacey and Kramers (1975) using the interpreted age of the sample. Percent errors of ²³⁸U/²⁰⁶Pb, ²³⁵U/²⁰⁷Pb, and ²⁰⁷Pb/²⁰⁶Pb (given in parentheses) were estimated using the method of Ludwig (1998) and reported at the 2σ confidence level.

20 m, respectively, and associated pyroclastic rocks (Maria and Hermes 2001; inset map in fig. 1). Major and trace element compositions indicate mildly alkaline character for both basalt and rhyolite.

The Wamsutta Formation has long been considered to be solely Pennsylvanian in age even though floral evidence is inconclusive for most units stratigraphically lower than the Rhode Island coal measures. Discontinuous arkose underlying Wamsutta redbeds is interpreted as Westphalian B Pondville Conglomerate (Mutch 1968) that is fossiliferous only in its type locality in the Norfolk Basin (Shaler et al. 1899; Lyons et al. 1976). In the redbeds themselves, reported plant fossils come from strata "several hundred feet below the top of the [Wamsutta] formation and above the felsite flows" (Knox 1944, p. 132). The results presented represent the first direct age constraint on the basal stratigraphy of the Narragansett Basin.

U-Pb Geochronology

Wamsutta rhyolite (sample DH02-17-98) from a small outcrop on Cumberland Avenue, South Attleboro, Massachusetts (inset map in fig. 1), was collected for U-Pb zircon geochronology. The sample represents the lower of two flows separated by approximately 3 m of pyroclastic and volcanoclastic sedimentary interbeds. The rhyolite consists of 5%–10% anorthoclase phenocrysts up to 1 cm in length in a granophyric, devitrified matrix. Zircon (length : width ranging from 2.5 : 1 to 1.2 : 1) was extracted from this rock and analyzed using standard isotope dilution techniques. U-Pb isotopic data for five zircon fractions of one to four grains are listed in table 1 and plotted on the concordia diagram in figure 2.

Four of the five analyses define a linear array that yields an upper intercept date of $372.8 \pm 10.2/-0.6$

Ma with an MSWD of 1.64. The weighted mean ²⁰⁷Pb/²⁰⁶Pb date of these four is 373.8 ± 2.9 with an MSWD of 1.83. The linear array is anchored by two analyses that overlap concordia and yield weighted mean ²⁰⁶Pb/²³⁸U and ²⁰⁷Pb/²³⁵U dates of 373.2 ± 0.3 and 372.95 ± 0.6 Ma, respectively. Thus, we feel confident that a date of 373 ± 2 Ma (Late Devonian in time scale of Tucker et al. 1998) is a reasonable estimate of the age of volcanism. Also noteworthy are the unusually high uranium concentrations in the dated samples (857–3705 ppm in table 1).

Discussion

Episodic Tectonism in the Narragansett Basin. The Late Devonian age of rhyolite in the northwestern corner of the Narragansett Basin means that this part of the basin was tectonically active at least 60 m.yr. earlier than previously recognized. Documented ages in the basin thus range from 373 Ma to approximately 295 Ma, much longer than the 310–295 Ma range based on floral assemblages alone. Limited exposure precludes mapping contacts within the basin, so it is unknown whether the stratigraphic succession representing this interval is continuous or whether unconformities and/or faults disrupt the sequence. Because no floras older than Westphalian B to Stephanian have ever been reported in the basin, it seems improbable that a complete Carboniferous section is present. It is more likely that a major unconformity separates the Late Devonian volcanic rocks and interstratified redbeds of the Wamsutta Formation from fossiliferous late Pennsylvanian strata, which include both redbeds currently placed at the top of the Wamsutta Formation and the overlying Rhode Island Formation. If an unconformity is present, this further implies that the lowest rocks in the

Figure 2. U-Pb concordia plot for zircon fractions from Wamsutta rhyolite. Ages in Ma are marked on the concordia curve, and individual analyses are shown as 2σ error ellipses. Points on diagram are numbered to correspond with analyses in table 1. Age of volcanism based on these data is 373 ± 2 Ma.

Narragansett Basin record a previously undetected tectonic phase preceding late Pennsylvanian subsidence. On the basis of the bimodal and alkalic nature of the dated Wamsutta volcanic rocks, the early activity was most likely rifting accompanying widespread anorogenic magmatism in southeastern New England.

Proposed Rifting. The basalt and rhyolite of the Wamsutta Formation represent a mildly alkalic bimodal suite contrasting with Neoproterozoic calc-alkaline volcanic rocks of the nearby Avalonian basement (Hermes and Murray 1990). Trace element compositions of the Wamsutta rhyolites and basalts have been interpreted in terms of partial melting of separate sources (Maria and Hermes 2001). Our 373 Ma date for the Wamsutta rhyolite links it with the 380–370 Ma Scituate Igneous Suite (U-Pb zircon date of Hermes and Zartman 1985), which forms a NNE-trending belt across Avalonian magmatic rocks to the west (fig. 1). Although dominantly granite, the Scituate Igneous Suite is not bimodal because it contains rocks of intermediate composition as well as some mafic gabbro and diorite. In addition, Scituate rocks are more enriched in high field strength trace elements and exhibit a stronger alkalic signature compared with more transitional Wamsutta volcanics (fig. 3). Some of the Scituate granitic rocks contain mafic enclaves demonstrating that magma mixing was an operative process. Despite these petrogenetic differences, granite in the Scituate Igneous Suite resembles Wamsutta rhyolite in its high uranium concentrations (825–2347 ppm in Hermes and Zartman

1985), so we regard them as generally similar magmatic pulses within a more protracted Devonian magmatic episode between about 400 and 370 Ma. Other plutonic rocks known to have formed during this interval include the Salem gabbro-diorite, the Wenham Quartz Monzonite, and the Peabody Granite (fig. 1; U-Pb zircon ages in Zartman 1977; Hermes and Zartman 1985; Hepburn et al. 1998; Acaster and Bickford 1999). All of these rocks have subtle to pronounced alkalic signatures generally similar to the Scituate and Wamsutta igneous rocks.

We propose that the Wamsutta-Scituate magmatic pulse represents a Late Devonian culmination of activity that began with an influx of mantle-derived mafic magma recorded by the Salem Gabbro/diorite (Zdigh of Zen 1983), which has yielded dates of 392 and 378 Ma in localities north of Waltham, Massachusetts (Hepburn et al. 1998; Acaster and Bickford 1999; fig. 1). A small amount of this magma eventually penetrated cold, brittle crust in what is now the northwest corner of the Narragansett Basin and erupted to form the little fractionated Wamsutta basalts with enriched levels of incompatible trace elements (Maria and Hermes 2001). Crustal underplating of mafic magma si-

Figure 3. Log-log plot of Zr versus Nb for selected igneous rocks in southeastern New England (after Hermes and Murray 1990). Members of the 380–370 Ma Scituate Plutonic Suite are enriched in high field strength elements like Nb and Zr, and they exhibit a large range of compositions that overlap the Late Devonian Wamsutta rhyolite and other suspected mid-Paleozoic volcanics including those at Spencer Hill (R.I.) and the Blue Hills (Mass.). Neoproterozoic volcanic rocks of calc-alkaline affinity are notably lower in high field strength elements.

multaneously induced melting within the crust to produce felsic magma that alternated with basalt to form the 373 Ma Wamsutta rhyolite. Continued melting generated larger volumes of felsic magma that ponded at depth to fractionate more extensively and mix with mafic magma, thus forming the diverse Scituate Igneous Suite. The enriched high field strength trace elements in these rocks compared with the Wamsutta volcanics may have resulted from more extensive fractionation combined with volatile fluxing of trace elements in the deeper, slower cooling magmatic reservoirs. This plutonism may have extended into Mississippian time on the basis of individual zircon fractions from Scituate and related rocks with $^{207}\text{Pb}/^{206}\text{Pb}$ dates as young as 344 Ma (Hermes and Zartman 1985). Even so, the Wamsutta-Scituate magmatism appears to record tectonic events unrelated to late Pennsylvanian sedimentation that produced the Rhode Island Formation coal measures some 35 m.yr. later.

The Late Devonian magmatic history in the northwestern portion of the Narragansett Basin and vicinity suggests similarities with coastal Maine, where mid-Paleozoic alkalic plutons have been interpreted as products of anorogenic magmatism within extensional or rift settings (Hogan and Sinha 1989). More detailed structural investigation is needed in southeastern New England, but a series of ductile shear zones consistent with rifting affects some Scituate rocks and a belt of adjacent rocks lying north of the pluton and paralleling its generally NNE elongation (fig. 1; Hermes et al. 1994). Although these shear zones are currently undated, they do not extend eastward into fossiliferous strata of the Narragansett Basin (Hermes et al. 1998), and so a pre-Pennsylvanian age seems likely. They show a normal sense of motion (Hamidzada 1988; Bettez 1998), and we interpret them to be localized in thermally weakened crust adjoining the subterranean continuation of the pluton. Several of these shears trend NNW parallel to the dike-like northern terminus of the pluton (fig. 1), suggesting stretching perpendicular to the plutonic axis. Areas flanking the belt of shear zones are interpreted to have pulled apart brittly to form discontinuous depocenters filled with volcanic and/or (meta)sedimentary rocks. These depocenters include undated strata in the North Scituate and Woonsocket Basins to the northwest of the ductile shears (PZb of Zen 1983; PZmc of Hermes et al. 1994; NSB and WB in fig. 1) and the Spencer Hill volcanics on the southeast (SH in fig. 1). Wamsutta volcanic rocks likewise occupy a flanking position east of the shear zones (boxed area north of South Attleboro in fig. 1), but

the original shape of this depocenter is masked by younger strata of the Rhode Island Formation.

Shear zones around the Scituate pluton and broader regional considerations further suggest that the proposed Late Devonian extension in southeastern New England was more complex than simple stretching accompanying the intrusion. The Wamsutta-Scituate magmatic interval between 380 Ma and 370 Ma also coincides with dextral shear along the Norumbega Fault System in eastern Maine (Ludman et al. 1999; West 1999) and other faults in Atlantic Canada (recent review in Hubbard 1999). The southward continuation of this faulting has tentatively been linked with right lateral movements on the Bloody Bluff Fault bounding the western margin of the southeastern New England Avalon Zone (Goldstein and Hepburn 1999; BBF in fig. 1), thus raising the possibility that transcurrent motions, too, were felt in crust thermally weakened by alkalic magmatism. Regional dextral motion across the 25-km-wide zone delimited by bold arrows in figure 1 is consistent with EW and NE trends of ductile shears located farthest north of the Scituate pluton. According to this interpretation, the EW-trending shears would mark the original extension direction, and NW-trending shears would reflect clockwise rotation of earlier directions. The proposed transcurrent zone can be traced northward along strike into other depocenters yielding evidence of Devonian age. These include the Newbury volcanics (NV in fig. 1), which contain sedimentary interbeds with Siluro-Devonian brachiopods (Shride 1976) and volcanic rocks east of Boston at Nantasket (Thompson and Grunow 2001).

Parallels with the Maritimes Basin. The history inferred to previously for the Narragansett Basin finds many parallels with the Maritimes Basin of Atlantic Canada, where deposition took place in half graben and extensional basins filled by Middle Devonian to Carboniferous sedimentary and associated volcanic rocks (Langdon and Hall 1994; Martel and Gibling 1996; Pascucci et al. 2000; Dunning et al. 2002). The oldest volcanic rocks include 389 ± 2 Ma welded tuff in the Guysborough area of northern mainland Nova Scotia (U-Pb zircon age of Cormier et al. 1995). Younger volcanic rocks of the Fisset Brook Formation in Cape Breton Island represent a bimodal, subaerial, within-plate assemblage closely resembling the Wamsutta Suite in the Narragansett Basin. Rhyolite in the Fisset Brook Formation is 373 ± 4 Ma (U-Pb zircon date of Barr et al. 1995). As in southeastern New England, plutons of similar age and petrologic affinity are more voluminous than volcanic rocks (Barr and Peterson

1998). The distribution and shape of these units, furthermore, suggests that magma was localized along major transcurrent to oblique slip faults (Dunning et al. 2002). Faults in mainland Nova Scotia localized renewed volcanism and plutonism between 365 and 354 Ma, synchronous with Horton Group deposition in latest Devonian to Tournasian time (Pe-Piper et al. 1998; Dunning et al. 2002). Decreasing subsidence and sedimentation rates in the younger Windsor and Mabou groups indicate thermal recovery from early rifting (St. Peter 1993; Rehill 1996). The final development of the Maritimes Basin commenced with renewed rapid subsidence above a basin-wide unconformity at the base of the Westphalian succession (Langdon and Hall 1994; Rehill 1996; Pascucci et al. 2000). Overlying upper Carboniferous and lower Permian rocks include redbeds and coal measures similar to those in the fossiliferous top of the Wamsutta Formation and the Rhode Island Formation in southeastern New England. The tectonic impetus for this subsidence has been viewed in different ways, but the overall sedimentation pattern is interpreted by some in terms of a foreland basin setting (Keppie 1982; Rehill 1996). A comparable interpretation for the Narragansett Basin treats late Pennsylvanian deposits as a clastic wedge of sediment subsequently overridden by thrust masses advancing eastward on the Lake Char and related faults (Wintsch and Sutter 1986; Wintsch et al. 1992).

Conclusions

Wamsutta rhyolite in the northwestern corner of the Narragansett Basin yields a U-Pb zircon date of 373 ± 2 Ma, indicating that this portion of the basin was tectonically active at least 60 m.yr. earlier than previously recognized. Late Devonian rifting

is favored by transitional alkalic rocks of the bimodal Wamsutta volcanic sequence and related alkalic plutons of the more voluminous 380–370 Ma Scituate Igneous Suite west of the basin. Extensile shear zones flanked by discontinuous depocenters in a belt continuing northward from and parallel to the NNE-trending plutonic axis provide structural evidence for rifting. Early-middle Carboniferous units are not reported above the Late Devonian volcanic rocks and interstratified redbeds, so regional subsidence resulting in fossiliferous Late Pennsylvanian sedimentary rocks represents a second, unrelated tectonic phase in the history of the basin. Redbeds currently assigned to the top of the Wamsutta Formation and overlying coal measures of the Rhode Island Formation developed during the second tectonic phase. The observed igneous rocks, basin stratigraphy, ages, and structural relationships in and around the Narragansett Basin show many similarities with the Devonian-Carboniferous Maritimes Basin in Atlantic Canada.

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