Broad-terrane Jurassic flood basalts across northeastern North America

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ABSTRACT

Early Jurassic tholeiitic lavas that flowed across Mesozoic basins of northeastern North America were comagmatic, as shown by their geochemistry, petrography, paleomagnetism, radiometric ages, and stratigraphy. The basin basalts are correlated with diabase dikes that intersect the basins but also extend far outside them. If the dikes represent feeders to fissure vents, a vast flood-basalt province must have extended across the rifted terranes of eastern North America in Early Jurassic time. The initial member of the basalt flood was the most uniform and widespread among present basin remnants of the basalts, but subsequent flows may have covered some areas farther from the basins. Other, younger Jurassic flood basalts have been described along submarine sections of the continental shelf and shelf break, and beneath Cretaceous coastal plain sediments in the southeastern United States. Across the inland Mesozoic rift terranes, the initial fissure eruptions produced a temporary basaltic plain perhaps 1600 km long and 200 to 400 km wide, or roughly 500 000 km^2, rivaling other great continental flood-basalt provinces.

INTRODUCTION

Recent work has demonstrated the presence of large volcanic provinces and wedge-shaped basalt bodies in offshore regions of eastern North America (Holbrook and Kelemen, 1993; Oh et al., 1995). Such basalts may be closely related to the production of new ocean crust during the Middle Jurassic opening of the central North Atlantic Ocean, and they explain geophysical features such as the east coast magnetic anomaly. Although continental margin lavas are major igneous features, they have been difficult to discern beneath thick covers of sediment and ocean water. Landward counterparts to these ocean-rift magmas are mainly plutons and dikes, with only limited (although notable) exposures of tholeiitic basalts within sections of early Mesozoic basins (Manspeizer, 1988).

Field and petrologic studies of Mesozoic diabase dikes in northeastern North America have shown that they are very large (up to 40 m wide and 250 km long), that they formed from the same types of magmas as the basalt flows, and that they were likely sources for the lavas and sills preserved within the basins (Philpotts and Martello, 1986; McHone, 1992). These great dikes have recently been mapped across large areas of New Hampshire, Maine, and New Brunswick between the Hartford and Fundy basins (McHone et al., 1995), and they form an important igneous link for the Early Jurassic basalts of those basins (Fig. 1). Because of these observations, the original extent of surface basalts across the rifted terranes of eastern North America must be tied to the distribution of the dikes rather than to the present geography of rift basins. Former locations of the Early Jurassic lavas can therefore be estimated from maps of the dikes and present-day basalts, from analyses of Late Triassic to Early Jurassic tectonism and topography, and from analogies with other flood-basalt provinces. These estimates indicate that Early Jurassic basalts were flooded over much of the Pangaean pre-Atlantic rift terranes.

The flood-basalt model is also a broad-terrane stratigraphic model, because it is linked to tectonic interpretations for the origins of Mesozoic basin strata. Related observations around the Newark, Hartford, and Fundy basins are emphasized in this paper. The flood-basalt interpretations are limited mainly by our poor knowledge of the regional Early Jurassic topography, which affected the directions and thicknesses of flows, and by the timing and nature of erosion that reduced the basins to their present pattern.

MESOZOIC BASINS AND BASALTS

The present distribution of eastern North American Mesozoic rift basins (Fig. 1) includes basins exposed along the eastern edge of the Applachian gravity gradient and a large group of basins that are covered by water and post-Jurassic sediments of the coastal plain (Hutchinson et al., 1988). The present basins patterns could be close to the original limits of early Mesozoic sediments and basalts (isolated basin model of Klein, 1969), or the sediments and basalts might have ranged more widely across the region previous to the formation of the basins (broad-terrane model of Russell, 1880). Sanders (1963) proposed that the northeastern basins were analogous to areas of the basin and range province of the southwestern United States; i.e., relatively discrete basins interconnected to wide-ranging sedimentary zones around uplifted basement ranges; later uplift completed the isolation of the basins.

Because Triassic strata in the basins have dips generally similar to their Jurassic strata, much of the border faulting that caused their half-graben tilting must have occurred late in the history of the basins (post-Hettangian), although fanglomerates and studies of sediment sources also show that the basin border faults were active throughout sedimentation (Klein, 1969). The truncated nature of basin strata beneath the onlap of the coastal plain shows that most of the tilting, uplift, and erosion of the rifted terrane was finished before the deposition of Cretaceous sediments.

The basin border faults and other faults thought to be genetically related are also mapped outside of the basins, leading to suggestions that Mesozoic basins were formerly more extensive. This idea was reinforced by the discovery of the small fault-bounded Middleton basin, a Triassic sediment remnant near Boston (Kaye, 1985). Along the western margin of the Fundy basin, the North Mountain basalt is apparently truncated by a major coast-parallel fault, but underlying Triassic sediments still remain in a few coastal places west of the basin (Schlische and Ackerman, 1995), and could have been more widely distributed across eastern New Brunswick.

From Virginia to Nova Scotia, the Mesozoic rift basins that preserve Jurassic strata also contain up to three distinctive horizons of quartz-normative tholeiitic basalts that have been correlated by age, stratigraphic position, chemistry, and petrography (see discussions by Philpotts and Martello, 1986; Olsen and Fedosh, 1988;

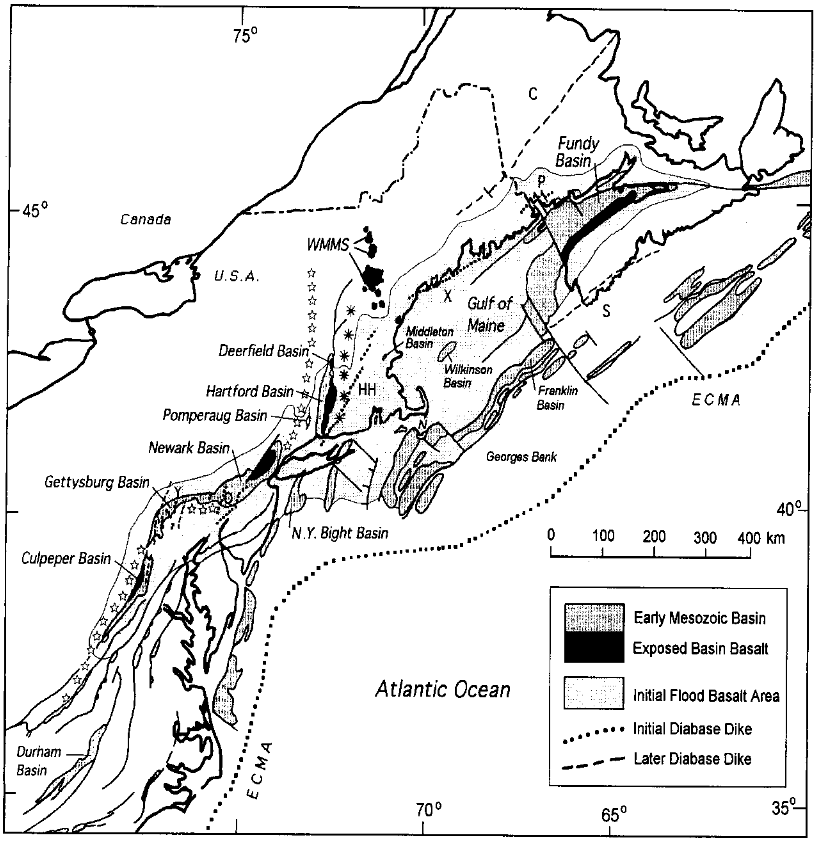

Figure 1. Mesozoic basins and rift features of northeastern North America, including proposed initial Early Jurassic flood basalt province. Basins are essentially as shown by Manspeizer (1988). Other labels (text references): S = Shelburne dike; C = Caraquet dike; X = Christmas Cove dike; HH = Higganum-Holden dike; P = Passamaquoddy Bay dike; N = Nantucket Island and adjacent Nantucket basin; ECMA = east coast magnetic high; WMMS = White Mountains magma series plutons; stars mark trend of Appalachian gravity gradient; asterisks mark Bronson Hills terrane.

Hozik, 1992; and Puffer, 1992). Although the rift basins contain varying amounts of older or younger sequences of sedimentary strata, stratigraphic evidence indicates that all of the basalts formed during a short interval spanning no more than 600 ka (Olsen and Fedosh, 1988). The most authoritative date for this magmatic episode is between 200 and 202 Ma (Dunning and Hodych, 1990; Hodych and Dunning, 1992). Cumulative thicknesses of the basalts vary above 250 m, and the initial-type basalt that covers the Fundy basin is at least 400 m thick in places (Dostal and Greenough, 1992). The stratigraphy also shows that the flows cannot be much younger than the Triassic-Jurassic boundary, or early Hettangian, and so they serve as an important marker for dating that boundary (Olsen and Fedosh, 1988).

The earliest member of these basaltic magmas comprises most of the sills that are common in the Culpeper, Gettysburg, Newark, and Hartford basins (Woodruff et al., 1995), and it is the only type known within the large Fundy basin (Fig. 1; Dostal and Greenough, 1992). Offshore basalt is present in the Nantucket basin (N, Fig. 1), and is suspected for other basins of the Long Island platform (Hutchinson et al., 1986). Basalts and sediments similar to those in the Hartford basin are found in the Pomparaug basin, which can be interpreted as a small basin remnant between the larger Hartford and Newark basins (Sanders, 1963). The Middleton basin of Kaye (1985) contains only Triassic sediments that predate the basalts.

Although Mesozoic sedimentary strata between present-day basins are now missing, there is evidence that Early Jurassic basalts extended outside of the basin borders. Highway construction in southern Connecticut temporarily exposed the faulted contact of Holyoke basalt against Paleozoic basement rocks along the southeastern fault border of the Hartford basin (Mikami and Digman, 1957, p. 69–78). In addition, boulders and cobbles of vesicular basalt are minor components of east-derived alluvial fan conglomerates in several places along the Hartford basin border fault. Basalt clasts are also known in Jurassic (post-lava flow) sedimentary rocks along the fault margins of the Fundy basin (Schlische and Ackerman, 1995) and the Newark basin (Sanders, 1963).

SOURCE DIKES

Subvolcanic feeders for the basin basalts are rarely obvious, but the flows and related sills were evidently erupted from fissures that in places are covered by younger strata. Such fissures are represented by diabase dikes that occur within the present sedimentary basins but also continue far outside them (Fig. 1; Smith et al., 1975; Philpotts and Martello, 1986). Specific dike-to-flow locations have been identified in the southeastern Hartford basin (Philpotts and Martello, 1986) and in the northern Culpeper basin (Woodruff et al., 1995). Basin lava vents and flow directions are mapped in New Jersey (Puffer and Student, 1992) and Massachusetts (Foose et al., 1968); in some cases their subsurface feeder dikes are not exposed but can be related to dikes exposed on trend in the region. In the Fundy basin, Papezik et al. (1988) hypothesized a major fissure eruption somewhere in its southern area to account for a massive northerly basalt flow.

The earliest of the basaltic magmas are notable for having nearly identical initial major and trace-element chemistry in every northern basin (Pegram, 1990; Puffer, 1992). This "initial Pangaean rift" (IPR) basalt as well as the subsequent basalts are correlated chemically with specific dikes (Fig. 2). Between Virginia and New Jersey, most IPR dikes are fairly short (a few kilometres to tens of kilometres) and have north to northeast trends, but they are relatively numerous (Fig. 1; Smith et al., 1975). In comparison, diabase dikes in New England and Atlantic Canada are fewer, but several examples are 20 to 40 m wide and extend more than 100 km (Fig. 1; Pe-Piper et al., 1992; McHone, 1992; McHone et al., 1995). Dikes of this size produced individual flows of the Columbia River basalt group that traveled more than 300 km and covered areas of at least 80 000 km^2 (Hooper, 1988).

The Higganum-Holden dike (HH in Fig. 1) is mapped about

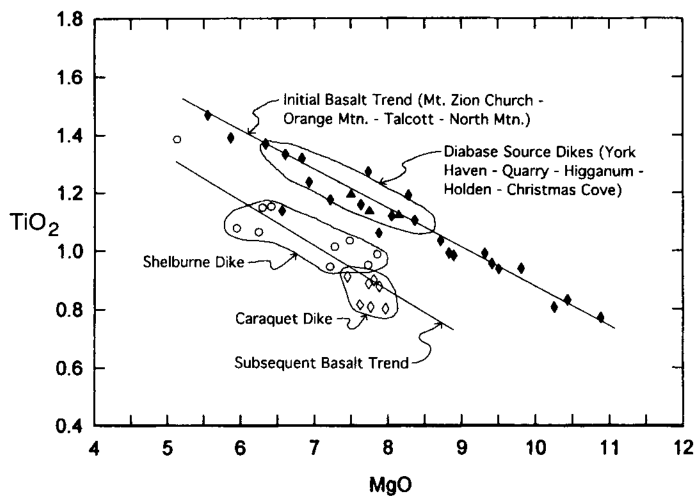

Figure 2. TiO_2-MgO plot for initial and subsequent Early Jurassic diabase dikes and basalts in eastern North America (other basalts are not shown). Solid triangles represent new analyses of Christmas Cove dike. Solid diamonds represent North Mountain basalt analyses from Dostal and Greenough (1992). Other sources: Smith et al. (1975); Papezik and Barr (1981); Greenough and Papezik (1986); Philpotts and Martello (1986); Puffer (1992).

250 km from western Long Island Sound into southeastern New Hampshire (Philpotts and Martello, 1986; Sundeen and Huff, 1992). The Higganum dike was correlated with the Fairhaven dike and the Talcott basalt within the Hartford basin by Philpotts and Martello (1986), who demonstrated a feeder-dike relation with this initial basalt. The Talcott basalt is up to 100 m thick, but it is eroded from the northern sections of the basin. The Higganum dike is covered by coastal plain sediments to the southwest, but where it continues in that direction it becomes adjacent to the Newark basin to the west and the New York Bight basin to the east (Fig. 1).

The Higganum-Holden dike has not (yet) been mapped through New Hampshire into southern Maine, but it may continue as the Christmas Cove dike, which crops out for at least 160 km along the coast of Maine (Hussey, 1971; McHone et al., 1995). The Christmas Cove dike is petrologically and physically identical to the Higganum-Holden dike (also see Fig. 2), except that its overall trend is more easterly in Maine. The similar Passamaquoddy Bay dike (P in Fig. 1) is mapped in segments for 30 km across Passamaquoddy Bay and along coastal New Brunswick, where it is offset by several northwest-trending faults (Dunn and Stringer, 1990). Papezik et al. (1988) suggested a northeastward flow of North Mountain basalt from a southern fissure, which is also consistent with the location of the Christmas Cove (X in Fig. 1) and Passamaquoddy Bay dikes. The Christmas Cove lava would also have spread across any low areas of the present Gulf of Maine as well as nonmountainous inland terranes of Maine and New Brunswick.

We should expect a similar overland flow from the huge Caraquet dike (C in Fig. 1), which extends more than 200 km southwestward across New Brunswick and into central Maine (Greenough and Papezik, 1986). However, no Mesozoic sedimentary rocks or lavas are reported from Maine or inland areas of New Brunswick. The distinctive "second basalt" magma type of the Caraquet dike (Fig. 2) is also not represented in the limited sample areas of the North Mountain basalt (Papezik et al., 1988), which implies that the Caraquet flow did not reach the present Fundy basin. Likewise, the Shelburne dike in southeastern Nova Scotia (Papezik and Barr, 1981) apparently did not contribute to the North Mountain basalt (Fig. 2), perhaps because of a topographic high between it and the Fundy basin in Early Jurassic time as well as today. However, basalt is known as a seismic reflection within the Franklin basin (Hutchinson et al., 1988), and the Shelburne dike (S in Fig. 1) is in position to be its source. Some overlap of the Shelburne magma with the North Mountain basalt should have occurred in basins southwest of Nova Scotia.

MESOZOIC BASALTIC LANDFORMS

Massive basalt eruptions occurred east of the exposed basins prior to and probably during the creation of the first ocean crust, between 185 and 175 Ma (Manspeizer, 1988). At least 100 000 km^2 of basalt underlies Cretaceous sediments across sections of the southeastern United States and continental shelf, where it merges with part of the thick basalt wedge that settled into the new continental margin (Oh et al., 1995). The final rift basalt occurs as a wedge along most of the eastern margin of the continent (Holbrook and Kelemen, 1993), as indicated by the east coast magnetic anomaly. Just inland from the hinge zone, Middle Jurassic flood basalts cover parts of the Georges Bank basin (Hurtubise et al., 1987; Hutchinson et al., 1988). The petrology of these final rift basalts is poorly known, and their ages are estimated to be at least 15 m.y. younger than the IPR continental flood basalts.

Inland from the Cretaceous coastal plain, no examples of Early Jurassic basalts are known to be preserved in surface exposures outside of early Mesozoic basins, as might be expected from rocks that weather and erode more rapidly than the underlying metamorphic basement. Figure 1 includes a rough estimate of the area covered by the initial Early Jurassic flood basalt, based on assumptions of moderate local relief, high-volume eruptions at the start of the Hettangian, and flow distances up to 400 km from source dikes (as demonstrated by Hooper, 1985, and Reidel and Tolan, 1992, for the Columbia River basalts).

The source dikes cross all terranes east of the present highlands of the Appalachian Mountains, and the flood basalts would have flowed over all varieties of bedrock surfaces where allowed by topography. As shown by border fanglomerates, interbasin uplift and border faulting were especially active during and after magmatism (Schlische and Ackermann, 1995), and basalts would have been quickly eroded from uplifted areas. Most or all interbasin basalts, and any accompanying sediments beneath or above the basalts, must have been removed during the ca. 100 m.y. interval before Cretaceous sediments spread across the present northeastern margin of North America, sediments that unconformably overlie basins onshore and offshore.

DISCUSSION

The evidence points to a nearly synchronous event of cogenetic fissure eruptions, with production of perhaps 50 000 km^3 of an initial rift magma along a linear zone from Virginia to Nova Scotia. This initial flood basalt (Fig. 1) could have extended much farther, because similar dikes and basalts are also known in eastern Newfoundland (Pe-Piper et al., 1992) and northwest Africa (Bertrand, 1991). Such uniformity requires a huge linear zone of eutectic-like mass melting (Puffer, 1992) under conditions similar to other flood-basalt events (Anderson et al., 1992). The limited chemical fractionation that is observed within various segments of the initial basalt has been explained by ponding at the base of the crust (Pegram, 1990), within the crust (Philpotts and Martello, 1986), or by fractional melting and magma flow (Puffer, 1992).

The slightly younger but also voluminous basalts that followed have their own distinctive characteristics and widespread distribution, adding to what must have become a very large plateau-like flood basalt terrane interspersed with basement highlands across northeastern North America. Basalts must have flowed around basin fault scarps and basement hills, and where dikes crossed highlands, downhill from those regions. Stream-deposited Triassic sediments could have been present over many areas between basins, and at least up to the time of the basalts, a version of the original broad-terrane hypothesis of Russell (1880) is suggested. Post-basalt faulting then accelerated the isolation of the basins and added extensive Jurassic fanglomerates. Jurassic faulting and uplift are responsible for the nearly complete erosion of the northern flood-basalt province, leaving only minor remnants preserved within today's basins.

ACKNOWLEDGMENTS

Anthony Philpotts, John Puffer, Jelle de Boer, Hervé Bertrand, Arthur Hussey, David West, and Nancy McHone have made valuable contributions to this work, but any misconceptions are my own. I thank Tony Philpotts, Peter Kelemen, and T. W. Sisson for their comments and critiques of the manuscript.

REFERENCES CITED

Anderson, D. L., Zhang, Y. S., and Tanimoto, T., 1992, Plume heads, continental lithosphere, flood basalts and tomography, *in* Storey, B. C., et al., eds., Magmatism and the causes of continental breakup: Geological Society of London Special Publication 68, p. 99–124.

Bertrand, H., 1991, The Mesozoic tholeiitic province of northwest Africa: A volcano-tectonic record of the early opening of the central Atlantic, *in* Kampunzu, A. B., et al., ed., Magmatism in extensional structural settings: New York, Springer Verlag, p. 147–191.

Dostal, J., and Greenough, J. D., 1992, Geochemistry and petrogenesis of the early Mesozoic North Mountain basalts of Nova Scotia, Canada, *in* Puffer, J. H., and Ragland, P. C., eds., Eastern North American Mesozoic magmatism: Geological Society of America Special Paper 268, p. 149–159.

Dunn, T., and Stringer, P., 1990, Petrology and petrogenesis of the Ministers Island dike, southwest New Brunswick, Canada: Contributions to Mineralogy and Petrology, v. 105, p. 55–65.

Dunning, G. R., and Hodych, J. P., 1990, U/Pb zircon and baddeleyite ages for the Palisades and Gettysburg sills of the northeastern United States: Implications for the age of the Triassic/Jurassic boundary: Geology, v. 18, p. 795–798.

Foose, R. M., Rytuba, J. J., and Sheriden, M. F., 1968, Volcanic plugs in the Connecticut Valley Triassic near Mt. Tom, Massachusetts: Geological Society of America Bulletin, v. 79, p. 1655–1662.

Greenough, J. D., and Papezik, V. S., 1986, Petrology and geochemistry of the early Mesozoic Caraquet dyke, New Brunswick, Canada: Canadian Journal of Earth Sciences, v. 23, p. 193–201.

Hodych, J. P., and Dunning, G. R., 1992, Did the Manicouagan impact trigger end-of-Triassic mass extinction?: Geology, v. 20, p. 51–54.

Holbrook, W. S., and Kelemen, P. B., 1993, Large igneous province on the U.S. Atlantic margin and implications for magmatism during continental breakup: Nature, v. 364, p. 433–436.

Hooper, P. R., 1988, The Columbia River basalt, *in* Macdougall, J. D., ed., Continental flood basalts: Boston, Kluwer Academic Publishers, p. 1–33.

Hozik, M. J., 1992, Paleomagnetism of igneous rocks in the Culpeper, Newark, and Hartford/Deerfield basins, *in* Puffer, J. H., and Ragland, P. C., eds., Eastern North American Mesozoic magmatism: Geological Society of America Special Paper 268, p. 279–308.

Hurtubise, D. O., Puffer, J. H., and Cousminer, H. L., 1987, An offshore Mesozoic igneous sequence, Georges bank basin, North Atlantic: Geological Society of America Bulletin, v. 98, p. 430–438.

Hussey, A. M., II, 1971, Geologic map and cross-sections of the Orrs Island 7 1/2 minute quadrangle and adjacent area, Maine: Maine Geologic Survey Map GM-2, 18 p.

Hutchinson, D. R., Klitgord, K. D., and Detrick, R. S., 1986, Rift basins of the Long Island platform: Geological Society of America Bulletin, v. 97, p. 688–702.

Hutchinson, D. R., Klitgord, K. D., Lee, M. W., and Trehu, A. M., 1988, U.S. Geological Survey deep seismic reflection profile across the Gulf of Maine: Geological Society of America Bulletin, v. 100, p. 172–184.

Kaye, C. A., 1985, Discovery of a Late Triassic basin north of Boston and some implications as to post-Paleozoic tectonics in northeastern Massachusetts: American Journal of Science, v. 283, p. 1060–1079.

Klein, G. deV., 1969, Deposition of Triassic sedimentary rocks in separate basins, eastern North America: Geological Society of America Bulletin, v. 80, p. 1825–1832.

Manspeizer, W., 1988, Triassic-Jurassic rifting and opening of the Atlantic: An overview, *in* Manspeizer, W., ed., Triassic-Jurassic rifting: New York, Elsevier, p. 41–79.

McHone, J. G., 1992, Mafic dike suites within Mesozoic igneous provinces of New England and Atlantic Canada, *in* Puffer, J. H., and Ragland, P. C., eds., Eastern North American Mesozoic magmatism: Geological Society of America Special Paper 268, p. 1–11.

McHone, J. G., West, D. P., Jr., Hussey, A. M., III, and McHone, N. W., 1995, The Christmas Cove dike, coastal Maine: Petrology and regional significance: Geological Society of America Abstracts with Programs, v. 27, no. 1, p. 67–68.

Mikami, H. M., and Digman, R. E., 1957, The bedrock geology of the Guilford 15-minute quadrangle and a portion of the New Haven quadrangle: Connecticut State Geological and Natural History Survey Bulletin no. 86, 99 p.

Oh, Jinyong, Austin, J. A., Jr., Phillips, J. D., Coffin, M. F., and Stoffa, P. L., 1995, Seaward-dipping reflectors offshore the southeastern United States: Seismic evidence for extensive volcanism accompanying sequential formation of the Carolina trough and Blake Plateau basin: Geology, v. 23, p. 9–12.

Olsen, P. E., and Fedosh, M. S., 1988, Duration of the early Mesozoic extrusive igneous episode in eastern North America determined by the use of Milankovich-type lake cycles: Geological Society of America Abstracts with Programs, v. 20, no. 1, p. 59.

Papezik, V. S., and Barr, S. M., 1981, The Shelburne dike, an early Mesozoic diabase dike in Nova Scotia: Mineralogy, petrology, and regional significance: Canadian Journal of Earth Sciences, v. 18, p. 1346–1355.

Papezik, V. S., Greenough, J. D., Colwell, J. A., and Mallinson, T. J., 1988, North Mountain basalt from Digby, Nova Scotia: Models for a fissure eruption from stratigraphy and petrochemistry: Canadian Journal of Earth Sciences, v. 25, p. 74–83.

Pegram, W. J., 1990, Development of continental lithospheric mantle as reflected in the chemistry of the Mesozoic Appalachian tholeiites, U.S.A.: Earth and Planetary Science Letters, v. 97, p. 316–331.

Pe-Piper, G., Jansa, L. F., and Lambert, R. St. J., 1992, Early Mesozoic magmatism on the eastern Canada margin: Petrogenetic and tectonic significance, *in* Puffer, J. H., and Ragland, P. C., eds., Eastern North American Mesozoic magmatism: Geological Society of America Special Paper 268, p. 13–36.

Philpotts, A. R., and Martello, A., 1986, Diabase feeder dikes for the Mesozoic basalts in southern New England: American Journal of Science, v. 286, p. 105–126.

Puffer, J. H., 1992, Eastern North American flood basalts, *in* Puffer, J. H., and Ragland, P. C., eds., Eastern North American Mesozoic magmatism: Geological Society of America Special Paper 268, p. 95–118.

Puffer, J. H., and Student, J. J., 1992, Volcanic structures, eruptive style, and post-eruptive deformation and chemical alteration of the Watchung flood basalts, New Jersey, *in* Puffer, J. H., and Ragland, P. C., eds., Eastern North American Mesozoic magmatism: Geological Society of America Special Paper 268, p. 261–277.

Reidel, S. P., and Tolan, T. L., 1992, Eruption and emplacement of flood basalt: An example from the large-volume Teepee Butte member, Columbia River Basalt group: Geological Society of America Bulletin, v. 104, p. 1650–1671.

Russell, I. C., 1880, On the former extent of the Triassic formation of the Atlantic states: American Naturalist, v. 14, p. 703–712.

Sanders, J., 1963, Late Triassic tectonic history of northeastern United States: American Journal of Science, v. 261, p. 501–524.

Schlische, R. W., and Ackermann, R. V., 1995, Kinematic significance of sediment-filled fissures in the North Mountain basalt, Fundy rift basin, Nova Scotia, Canada: Journal of Structural Geology, v. 17, p. 987–996.

Smith, R. C., II, Rose, A. W., and Lanning, R. M., 1975, Geology and geochemistry of Triassic diabase in Pennsylvania: Geological Society of America Bulletin, v. 86, p. 943–955.

Sundeen, D. A., and Huff, M. C., 1992, Petrography, petrology, and K-Ar geochronology of hypabyssal mafic and silicic Mesozoic igneous rocks in southeastern New Hampshire, *in* Puffer, J. H., and Ragland, P. C., eds., Eastern North American Mesozoic magmatism: Geological Society of America Special Paper 268, p. 75–94.

Woodruff, L. G., Froelich, A. J., Belkin, H. E., and Gottfried, D., 1995, Evolution of tholeiitic diabase sheet systems in the eastern United States: Examples from the Culpeper Basin, Virginia-Maryland, and the Gettysburg Basin, Pennsylvania: Journal of Volcanology and Geothermal Research, v. 64, p. 143–169.

Manuscript received June 5, 1995
Revised manuscript received January 16, 1996
Manuscript accepted January 26, 1996