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A LATE NEOPROTEROZOIC EASTERN LAURENTIAN SUPERPLUME: LOCATION, SIZE, CHEMICAL COMPOSITION, AND ENVIRONMENTAL IMPACT

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ABSTRACT. **A database consisting of 25 data-sets has been compiled that includes published chemical analyses of most known eastern North American occurrences of late Neoproterozoic (Vendian) flood basalt and dike swarms together with some new geochemical data. Four additional eastern North American basalt occurrences of probable early Paleozoic age were also examined. The Vendian occurrences comprise the Central Iapetus magmatic event of Eastern North America which extends from the Long Range dikes of Labrador and Newfoundland to the Catoctin flood basalts of Virginia and includes the Grenville dike swarm of Ontario and Quebec. The strike of the Vendian dike swarms converge near a major gravity and magnetic anomaly at Sutton Mountain, Quebec. The chemical composition of the Vendian basalts and diabase dikes plotted onto spider diagrams normalized to the composition of the silicate earth can be subdivided into a tight cluster of parallel lines displaying HFSE enrichment and a more diverse group that is less enriched. The tight grouping of the enriched cluster suggests a mutual genetic relationship consistent with mantle plume derivation based largely on chemical similarity to standard Ocean Island Basalt (OIB). However, detailed examination of this eastern Laurentian OIB related cluster (LOIB) reveals regional variations in chemical composition, particularly TiO_2 and Zr, that can be contoured to delineate a narrow lens shape with peak concentrations centered close to the Sutton Mountain triple junction. The central portion of the LOIB is geochemically the same as superplume derived basalt. Radiometric evidence indicates that the LOIB superplume magmatic activity peaked at about 550 Ma.**

The less enriched group geochemically resembles some of Earth's larger continental flood basalts, such as the Columbia River basalt province, derived from a subcontinental lithospheric mantle source mixed with magma from a mantle plume source. Radiometric and paleomagnetic evidence indicates that this less enriched group is about 615 to 564 Ma and probably extruded out of rifts that preceded the break-up of Pannotia. This mid-Vendian magmatism is consistent with the early stages of deep mantle plume upwelling but may be genetically independent of the superplume magmatism that followed.

The four early Paleozoic basalt suites examined are interpreted as post-LOIB, Iapetan Ocean ridge basalt accreted onto eastern Laurentian or perhaps basalt extruded from transform faults that intersected the trailing edge of Laurentia.

If LOIB magmatism was generated by a superplume head, there may be important environmental implications. The LOIB event may have been partially responsible for considerable mantle outgassing, particularly carbon dioxide and nutrients, global warming, and major increases in the growth rate and deposition of marine life that occurred during the early Cambrian.

INTRODUCTION

Burke and Dewey (1973) were among the first to point out that the strike of eastern North American dike swarms of late Proterozoic age converge at a point (a

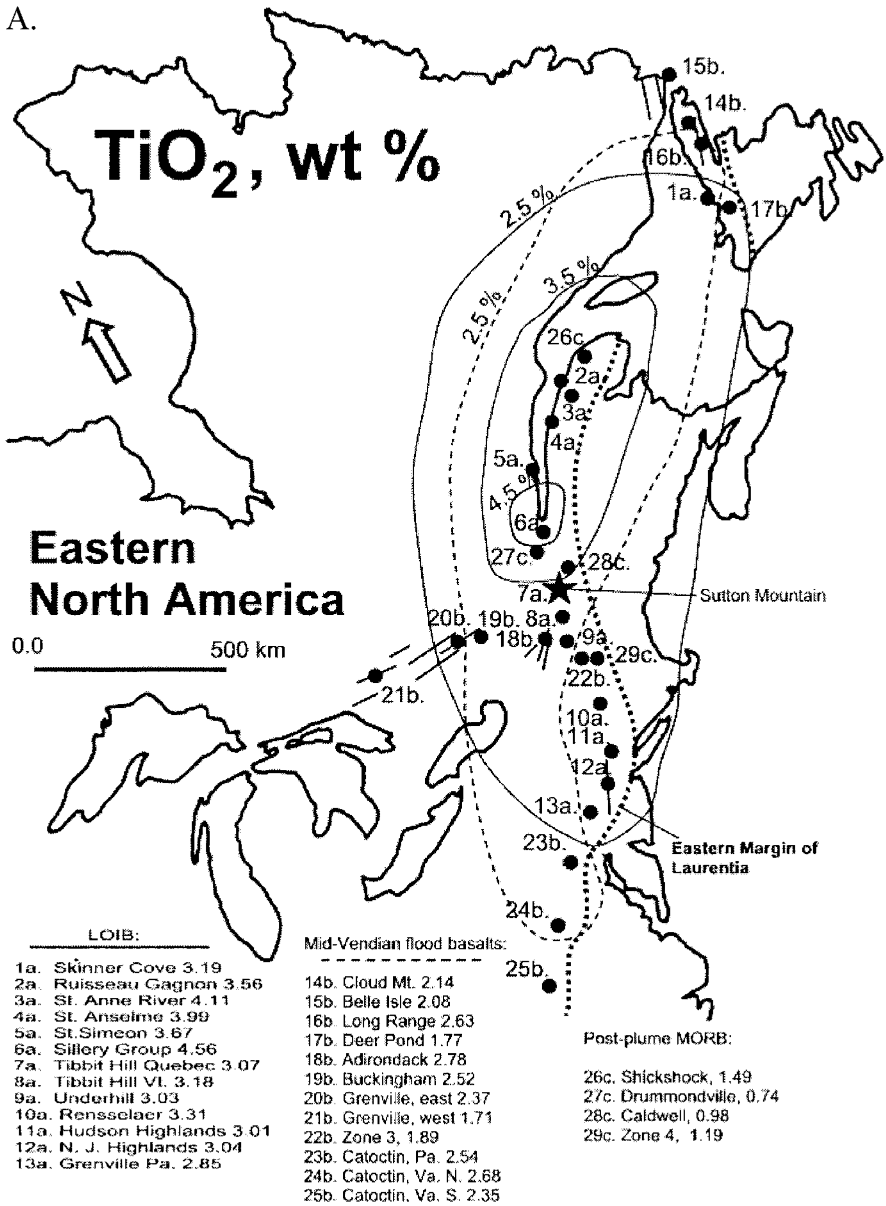

Fig. 1. The location of Eastern Laurentian rock suites listed on table 1 that chemically resemble OIB basalt (the LOIB group are plotted with an "a," those resembling plume related continental flood basalts are plotted with a "b," and those resembling N-MORB with a "c." The eastern edge of Laurentia defined as the eastern edge of the Appalachian miogeocline is based on the map of Williams and Hatcher (1982). Contours drawn around LOIB type basalt locations are solid lines; contours around plume related continental flood basalts are dashed lines. (A.) TiO_2 concentrations from tables 2 to 4, (B.) Zr concentrations from tables 2–4.

triple junction) that they suggested was close to Montreal, Canada. In addition to diabase dikes, the southern arm of the proposed triple junction includes basalts such as the Tibbit Hill, the Rensselaer, and the Catoctin (fig. 1) that are exposed along the Appalachian Mountains. The western arm is defined by the Grenville Dike Swarm, and

B.

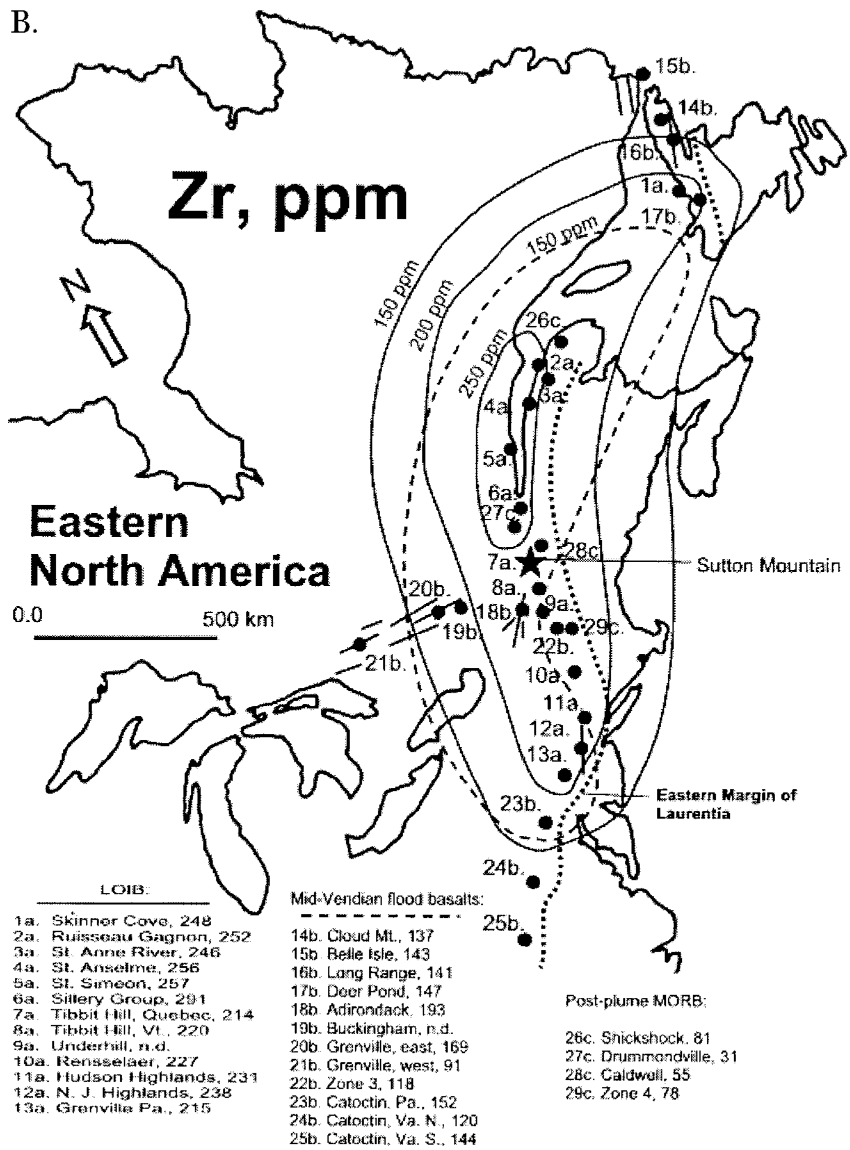

Fig. 1 (continued)

the Northern arm extends through the Ruisseau Gagnon basalts of the Gaspe Peninsula and the Long Range dikes and flows of Labrador and Newfoundland (fig. 1). More recent choices for the location of the triple junction include a point east of Tibbit Hill, Quebec that Kumarapeli and others (1981), Coish and Sinton (1992), and St. Seymour and Kumarapeli (1995) describe as the Sutton Mountain triple junction (fig. 1) and a point near Saint John, New Brunswick that Ernst and Buchan (1997) propose after adjusting for about 100 km of westward Appalachian thrusting. Ernst and Buchan (1997) refer to the basaltic rocks that define this triple junction as the "Central Iapetus magmatic event" associated with the opening of the Iapetus Ocean and further suggest that the radiating pattern may indicate that rifting was caused by a mantle plume in agreement with earlier proposals made by St. Seymour and Kumarapeli (1995).

The results presented in this paper support the concept that a mantle plume or perhaps two plumes were involved in the Neoproterozoic rifting of Laurentia. On the basis of geochemical evidence, an attempt is made to estimate the shape, sphere of influence, and environmental impact of this mantle plume or plumes. The data used was compiled primarily from published geochemical analyses of basaltic rock suites of probable Vendian age (650-544 Ma) exposed throughout eastern Laurentia (table 1) and consist of three groups of average composition and standard deviation calculations (tables 2-4). Two additional averages listed in table 1 were compiled from new chemical analyses of: (1) five diabase dikes intruded into Grenville rock from the Reading area of Pennsylvania at sites described by Smith (1973), and (2) eight samples of northern Catoctin basalt collected along the South Mountain section of the Blue Ridge province of Adams and Franklin Counties Pennsylvania at locations (field-trip stops 3 and 4) described by Smith and others (1991).

Most of the geochemical data pertaining to the Central Iapetus magmatic province can be separated into two groups when plotted onto spider diagrams (figs. 2 and 3) normalized to the composition of the silicate earth (McDonough and Sun, 1995) and arranged according to incompatibility in oceanic basalts (Sun and McDonough, 1989). The average chemical compositions of thirteen of the eastern Laurentian basaltic rock occurrences (table 2) plot as a tight cluster of approximately parallel lines that overlap the standard ocean island basalt (OIB) of Sun and McDonough (1989), (the LOIB group, fig. 2).

A second group of twelve Central Iapetus basaltic rock suites (table 3) is slightly older than the LOIB group, is less enriched in incompatible elements, is compositionally more diverse than the LOIB group, and is geographically more widespread (fig. 1). In general, the second group plotted onto silicate earth normalized spider diagrams (fig. 3) compositionally resembles some of Earth's larger plume related continental flood basalt provinces (Puffer, 2001) such as the quartz tholeiitic Columbia River Basalt (Hooper and Hawkesworth, 1993). Evidence is presented suggesting that this quartz tholeiitic flood basalt group was genetically related to the early stages of a large mantle plume upwelling under a stationary reassembled Rodinian plate (Pannotia) as it was undergoing stretching and rifting before its break-up during late-Vendian time (Soper, 1994; Dalziel, 1997). However, if Laurentia was disconnected from the mid-Vendian plume source, as suggested by the paleomagnetic based interpretation of Cawood and others (2001), the source of late Vendian basaltic magmatism was a second plume; the LOIB superplume.

Evidence is also presented indicating that each of four eastern Laurentian basalt suites of questionable late Neoproterozoic to early Paleozoic age (tables 1 and 4) represents post-plume volcanism.

Particularly meaningful for distinguishing the compositional groups are the levels of the high field strength elements (HFSEs) particularly TiO_2 and Zr generally regarded as resistant to the metasomatic and hydrothermal effects common to most if not all of the Neoproterozoic and early Paleozoic basalts of eastern Laurentia. The standard deviation calculations (tables 1-5) with few exceptions show limited TiO_2 variation within each suite of rocks suggesting a limited fractionation range. In addition, despite high degrees of alteration among several of the rock suites and, therefore, much less reliable MgO data, the generally low MgO standard deviations support a limited fractionation range in most cases. However, a wide range of MgO and TiO_2 data with bimodal distributions was observed in two suites, the Skinner cove basalts of Newfoundland (tables 2 and 5) and the Grenville Dike Swarm of southern Ontario and Quebec (table 3), which permitted the separation of mafic relatively

TABLE 1

Eastern Laurentian late Neoproterozoic basaltic rock suites

A. LOIB Group	Location (N to S)	Geochemical Source	Chronology
Skinner Cove basalt	West Newfoundland	Baker, 1979	550.5+/-3 Ma, U-Pb, McCausland and others, 1997
Ruisseau Gagnon basalt	Matane, Gaspe Peninsula	Thivierge, 1992	Tibbit Hill correlative (Camire and others, 1995)
Ste-Anne River transitional basalt	central Gaspe Peninsula	Camire and others, 1995	Tibbit Hill correlative (Saint-Julien and Hubert, 1975)
St.-Anselme basalt	St.-Fabien, Quebec	La Fleche and others, 1993	Hadrynian, (LaFleche and others, 1993)
Grenville, St-Simeon dikes	St.-Simeon, Quebec	La Fleche and others, 1993	St.-Anselme geochemical correlative (LaFleche and others, 1993)
Sillery alkali basalts	St.-Flavien, Quebec	Vermette and others, 1993, and Olive and others, 1997	Tibbit Hill correlative, (Olive and others, 1997)
Tibbit Hill basalt, Quebec	Sutton Mt. Quebec	Abdel-Rahman and Kumarapeli, 1999	554 +/- 4 Ma, (Kumarapeli and others, 1989)
Tibbit Hill basalt, VT	North Vermont	Coish and others, 1985	554 +/- 4 Ma, (Kumarapeli and others, 1989)
Underhill basalts and dikes?	Central Vermont	Coish and others, 1985	Intrudes Camels Hump Gr. (Coish and others, 1985)
Rensselaer basalt	Albany, New York	Ratcliffe, 1987a	Tibbit Hill correlative, (Ratcliffe, 1987a)
Hudson Highlands dikes	Peekskill, New York	Ratcliffe, 1987b	Late Proterozoic / early Paleozoic (Ratcliffe, 1987b)
New Jersey Highlands dikes	NW New Jersey	Volkert and Puffer, 1995	Late Proterozoic (Volkert and Puffer, 1995)
Grenville dikes, PA	Reading, PA	This study, (Hull and others, 1988)	New Jersey Highlands correlative
B. Mid-Vendian Flood Basalt Group	**Location (N to S)**	**Geochemical Source**	**Chronology**
Cloud Mountain basalt	West Newfoundland	Strong, 1974	fed from Long Range dikes, (Strong, 1974)
Belle Isle, basalt flows and dikes	East Labrador	Strong, 1974	fed from Long Range dikes, (Strong, 1974)
Long Range dikes	Lab. and Newfoundland	Strong, 1974	615 Ma, U/Pb, (Kamo and others. 1989)
Deer Pond basalt	West Newfoundland	Williams and others, 1985	in 602 +/- 10 Ma, U/Pb Hughes Lake Complex, (Williams and others, 1985)
Grenville dikes, west half	Eastern Ontario	St. Seymour and Kumarapeli, 1995	590 +/- 2 Ma, U/Pb, (Kamo and others, 1995)
Grenville dikes, east half	S Quebec & SE Ontario	St. Seymour and Kumarapeli, 1995	590 +/- 2 Ma, U/Pb, (Kamo and others, 1995)
Buckingham basalts	Central Ottawa Graben	La Fleur and Hogarth, 1981	573 +/- 32 Ma, K/Ar La Fleur and Hogarth, 1981)
Adirondack, dikes	NE Adirondacks, NY	Coish and Sinton, 1992	588 Ma, (Isachsen and others, 1988; Coish and Sinton, 1992)
Zone 3 (Hazens Notch + Hancock)	Northwest Vermont	Coish and others, 1991	571 +/- 5 Ma U/Pb, (Walsh and Aleinikoff, 1999)
Catoctin basalt PA	Waynesboro, PA	This study, (Smith and Barns, 1994)	564 +/- 9 Ma, U/Pb, (Aleinikoff and others, 1995)
Catoctin basalt, VA, north	Shenandoah Park, VA	Reed and Morgan, 1971	564 +/- 9 Ma, U/Pb, (Aleinikoff and others, 1995)
Catoctin basalt, VA, south	Linchburg, Virginia	Wang and Glover, 1997	564 +/- 9 Ma, U/Pb, (Aleinikoff and others, 1995)
C. Vendian / Paleozoic? Group	**Location**	**Geochemical Source**	**Chronology**
Caldwell basalt	Etchemin River, Quebec	Bedard and Stevenson, 1999	Hadrynian to Early Cambrian, (St.Julien and Hubert, 1975)
Zone 4 (Stowe + Ottauquechee)	Northwest Vermont	Coish and others, 1991	470 to 554 Ma (Coish and others, 1991)
Drummondville subalkaline basalt	South Quebec	Vermette and others, 1993 and Olive and others, 1997	Camb. to mid-Ord., (Vermette and others, 1993)
Shickshock basalt	Gaspe Peninsula	Camire and others, 1995	erupted during 550-615 Ma rifting, (Camire and others, 1995)

TABLE 2

Chemical composition of late Vendian LOIB basalt group

Name	Skinner Cove		Ruisseau		Ste-Anne River		St-Anselme		St-Simeon		Sillery Group		Tibbit Hill	
Location	Newfoundland		Gaspe P.		Gaspe P.		Quebec		Quebec		Quebec		Quebec	
n , s.d.	43	s.d.	23	s.d.	8	s.d.	2	s.d.	5	s.d.	14	s.d.	3	s.d.
SiO_2	48.11	3.5	48.84	1.6	49.96	2.6	50.10	2.8	49.24	0.5	45.50	4.6	47.86	0.3
TiO_2	3.19	0.8	3.56	0.8	4.11	0.8	3.99	0.5	3.67	0.3	4.56	0.9	3.07	0.3
Al_2O_3	16.33	1.4	16.60	0.9	15.28	1.4	13.10	0.4	15.00	0.8	11.54	1.7	16.93	0.4
FeO	11.32	1.6	13.85	1.3	13.11	1.9	16.33	0.8	13.84	1.6	15.12	3.9	14.44	2.2
MnO	0.26	0.1	0.25	0.0	0.26	0.1	0.27	0.1	0.30	0.1	0.26	0.2	0.24	0.0
MgO	5.84	2.2	5.61	1.3	6.58	1.4	4.37	0.2	5.15	0.9	8.32	2.5	6.27	1.7
CaO	8.04	2.9	6.10	1.4	5.30	0.6	6.88	0.5	7.47	1.9	10.01	3.1	5.08	1.9
Na_2O	4.03	1.2	4.06	0.6	4.52	0.8	3.64	0.8	3.13	0.2	2.79	1.6	4.74	0.5
K_2O	1.87	1.3	0.41	0.5	0.19	0.3	0.35	0.3	1.60	0.6	0.73	1.1	0.84	0.4
P_2O_5	1.01	0.3	0.71	0.3	0.70	0.2	0.96	0.3	0.59	0.1	1.15	1.8	0.52	0.1
Rb	20	14			8	5	13	11	39	22	13	11	21	12
Ba	883	1041					2469	3365	574	192	540	519	594	0
Sr	722	224	296	109	180	112	484	42	345	87	497	310	358	409
Th			1.4		1.7		2.4	0.2	1.8	0.3	3.8	1.7	0.6	0
Zr	248	81	252	78	246	46	256	175	257	25	291	107	214	36
Nb	74.7	22.3					28.0	0.7	23.0	4.7	55.3	23.8	24.0	8.5
Ni	46	57	82	39	37	21	28	12	82	51	243	131	117	59
Cr	45	69			69	75			68	41	243	71	175	37
La	101	22	24	9	21	4	33	5	32	7	41	19	26	6
Ce	160	38	55	21	54	11	78	14	69	12	91	41	61	15
Nd			34	12	34	6	51	8	41	8	27	27	33	6
Sm			8.5	2.7	9.0	1.6	11.4	2.2	9.4	1.3	10.5	4.4	7.5	1.5
Eu			2.7	0.7	3.2	0.5	3.9	0.8	3.3	0.3	3.2	1.2	2.5	0.4
Tb			1.2	0.3	1.4	0.2	1.8	0.4	1.5	0.2	1.2	0.2	1.0	0.2
Yb			3.2	0.7	4.1	0.9	4.7	0.6	3.5	0.6	1.7	0.5	3.0	0.6
Lu			0.5	0.1	0.6	0.2	0.7	0.1	0.5	0.1	0.2	0.1	0.5	0.0
Y	24	3	42	8	48	9	52	9	43	8	29	10	34	5

Major element data are recalculated to 100 percent anhydrous with ferrous and ferric iron recalculated to FeOt.

Sources of chemical data are listed in table 1.

primary subsets of samples from relatively fractionated subsets. The mafic Skinner cove subset is particularly mafic (table 5) and resembles superplume basalt.

THE LATE-VENDIAN (LOIB) GROUP

The LOIB group (table 2) includes 13 chemically analyzed occurrences of Vendian eastern North American basaltic rocks. This group of subaerial continental flood basalts and submarine pillow basalts is defined by its restricted range of chemical composition resembling OIB basalt (fig. 2). The interval from Nd through Y (fig. 2) is a particularly closely spaced cluster, and each member of the group contains Ti, Tb, and Y levels that equal or exceed OIB levels. Each of the LOIB rock suites has been either dated radiometrically to lie within a 554 to 550 Ma range or correlate with dated 554 to 550 Ma late Vendian rocks on the basis of compelling stratigraphic evidence (table 1). The youngest radiometrically dated extrusions are found at Skinner Cove, Newfoundland dated at 550 Ma (McCausland and others, 1997) while the oldest are the Tibbit Hill basalts dated at 554 Ma (Kumarapeli and others, 1989).

Geologic setting.—Each of the dike swarms and basalts of the LOIB group are located along the eastern margin of Laurentia (fig. 1). The suites consisting of

Table 2

(continued)

Name	Tibbit Hill		Underhill		Rensselaer		Hudson Highlands		Highlands		Grenville dikes	
Location	Vermont		Vermont		New York		New York		New Jersey		Pennsylvania	
n , s.d.	9	s.d.	34	s.d.	9	s.d.	16	s.d.	35	s.d.	5	s.d.
SiO_2	49.72	3.0	47.54	2.0	50.00	1.8	49.98	0.8	50.27	1.4	50.79	0.7
TiO_2	3.18	0.1	3.03	1.0	3.31	1.1	3.01	0.4	3.04	0.5	2.85	0.4
Al_2O_3	15.70	0.9	15.22	1.4	13.25	1.6	13.45	0.6	13.48	1.0	13.96	0.7
FeO	12.85	1.7	13.87	1.6	15.36	3.0	14.05	0.8	13.86	1.3	13.73	1.7
MnO	0.11	0.1	0.22	0.1	0.23	0.0	0.22	0.0	0.23	0.1	0.22	0.0
MgO	5.97	2.9	7.22	1.7	5.52	0.9	5.72	0.7	5.19	1.1	5.67	1.0
CaO	6.82	2.1	8.59	1.4	8.23	1.5	9.13	1.0	8.75	1.3	8.69	1.0
Na_2O	4.56	1.8	3.12	0.8	2.61	0.7	2.71	0.7	3.02	0.6	2.49	0.5
K_2O	0.70	0.6	0.71	0.5	1.10	0.7	1.10	0.5	1.46	0.6	1.18	0.2
P_2O_5	0.39	0.1	0.38	0.2	0.38	0.1	0.61	0.2	0.70	0.4	0.42	0.1
Rb	17	21			40	15	38	24	47	16	46	13
Ba	201	162			354	151	315	231	487	289	415	67
Sr	147	96			468	131			320	104	330	45
Th	2.4	0.8	1.8	1.5	1.6	0.5	1.8	0.5				
Zr	220	32			227	54	231	47	238	68	215	10
Nb	29.0	4.1							35.3	13.3	24.0	6.0
Ni	78	29			101	27			26	17	51	17
Cr	93	22	99	75	105	136	71	61	58	32	59	16
La	24	6	24	20	19	8	21	7	29	11	19	2
Ce	58	11	65	54	43	18	48	13	56	12	42	5
Nd	30	5	37	29	29	9	34	9			28	5
Sm	7.6	0.8	8.2	5.4	7.6	2.7	7.9	1.7	8.7	2.2	8.0	1.6
Eu	2.4	0.4	2.7	1.6	2.2	0.7	2.5	0.7	3.0	0.9		
Tb	1.3	0.2	1.2	0.7	1.1	0.3	1.3	0.2	1.0	0.4		
Yb	3.1	0.4	3.4	1.1	3.1	0.7	3.5	0.7	3.5	0.5		
Lu	0.5	0.1	0.5	0.1	0.5	0.1	0.5	5.5	0.6	0.1		
Y	33	5							30	11	32	4

extrusive flows (table 1) are interbedded with Vendian sediments or were extruded onto Proterozoic basement. Vendian sediments interbedded with LOIB basalt flows are typically coarse-clastics deposited in an intra-continental to continental margin environment. For example, the Skinner Cove basalts of Newfoundland rest uncomformably on granite gneiss basement (Baker, 1978). The Sillery Group basalts in Quebec are interbedded with argillaceous shales, siltstones, feldspathic arenite, and graded-bedded rudite (Olive and others, 1997). The Tibbit Hill basalt in Quebec-Vermont is interbedded with metagraywacke, conglomerates, arkose, and phillite (Coish and others, 1985); and Ratcliffe (1987a) has found that the Rensselaer basalt of New York is also interbedded with metagreywacke that thickens and coarsens to the west and contains detritus of probable eastern North American Proterozoic provenance. The Rensselaer basalt includes massive flows that may be sub-aerial, but it becomes pillowed to the east.

Petrography.—The component members of the LOIB group (table 2) range from slightly to highly metamorphosed. The zeolite facies metamorphic grade of the Skinner Cove basalt is characterized by pervasive precipitation of analcime and quartz, although much of the plagioclase and pyroxene content is only slightly altered (Baker, 1978; Cawood and others, 2001). The Skinner Cove suite, including the 43 samples averaged for table 2, is particularly diverse and includes alkalic basalt, trachybasalt,

TABLE 3

Chemical composition of mid-Vendian Eastern Laurentian flood basalt group

Name	Cloud Mountain		Belle Isle		Long Range		Deer Pond.		Grenville West		Grenville East		Buckingham	
Location	Newfoundland		Labrador		Newfound		Newfoundland		Ontario		Ontario		Quebec	
n , s.d.	11	s.d.	21	s.d.	14	s.d.	3	s.d.	4	s.d.	4	s.d.	4	s.d.
SiO_2	49.91	1.4	50.96	1.2	48.25	0.7	50.53	1.9	49.00	0.2	50.57	2.2	52.62	0.9
TiO_2	2.14	0.6	2.08	0.5	2.63	0.7	1.77	0.4	1.71	0.3	2.37	0.6	2.52	0.4
Al_2O_3	14.88	0.8	14.64	0.9	14.34	1.5	14.68	0.8	14.36	0.6	14.80	0.9	15.72	0.6
FeOt	13.38	1.4	12.27	1.4	13.99	1.6	13.61	1.0	14.73	1.2	13.41	2.5	9.97	0.8
MnO	0.23	0.0	0.22	0.0	0.25	0.1	0.30	0.1	0.00				0.12	0.1
MgO	6.37	0.9	6.05	1.3	6.25	0.7	7.74	1.6	6.60	1.0	5.00	1.8	5.44	0.5
CaO	8.31	2.0	9.21	2.1	11.12	0.9	6.64	1.2	10.90	0.7	9.79	1.6	5.06	2.1
Na_2O	3.21	0.9	3.17	1.1	2.35	0.2	3.58	1.2	2.27	0.1	2.51	0.8	3.15	1.0
K_2O	1.35	0.7	1.13	0.6	0.54	0.2	0.96	0.5	0.30	0.1	1.05	1.2	4.54	2.0
P_2O_5	0.22	0.1	0.27	1.1	0.29	0.1	0.18	0.1	0.14	0.0	0.51	0.4	0.87	0.3
Rb	39	17	32	13	20	3	37	26	10	2	17	9		
Ba	358	166	422	160	275	114	152	124	46	48	420	33		
Sr	204	90	227	77	214	30	242	164	191	23	412	428		
Th									4.50	1.0	3.40	2.0		
Zr	137	31	143	47	141	30	147	56	91	18	169	64		
Nb							8.6	5.7	5.0	1.4	10.0	4.6		
Ni	66	15	60	27	77	25	70	30	90	21	52	32		
Cr	69	29	119	46	102	39	117	93	118	38	67	27		
La											5.7			
Ce											16.3			
Nd											12.4			
Sm											4.1			
Eu											1.5			
Tb														
Yb											2.2			
Lu														
Y							38	12	26	4	38	10		

Major element data are recalculated to 100 percent anhydrous with ferrous and ferric iron recalculated to FeOt.

Sources of chemical data are listed in table 1.

s.d.* individual sample analyses were not published

pyroxene-phyric basalt, and ankaramite flows. This basalt suite is associated with highly fractionated trachyte flows, pyroclastic layers, and limestone beds (Baker, 1978).

The Ste-Anne River basalts and the nearby Ruisseau Gagnon basalts from the Ste-Anne River Nappe of Quebec (fig. 1) are chemically (table 2) and petrographically similar, although the St-Anselme basalts are relatively altered. The Ste-Anne River flows are described by Camire and others (1995) as subgreenschist facies massive or amygdaloidal and pillowed basalts with well preserved labradorite (An_{65}) and augite phenocrysts that are partially or wholly pseudomorphosed by albite and chlorite, respectively. The St-Anselme samples analyzed by LaFleche and others (1993) are from the interiors of pillows and consist largely of albitic plagioclase, possible relics of pyroxene, and abundant epidote.

Vermette and others (1993) describe the basalt of the Sillery Formation, Quebec (fig. 1) as fine to medium grained vesicular and amygdaloidal massive flows, composed largely of sericitized plagioclase (An_{35}) and chloritized volcanic glass with phenocrysts of plagioclase (An_{35}), altered olivine, relatively unaltered augite, and kaerssutite. They conclude that the basalt underwent very low-grade metamorphism.

The Tibbit Hill and Rensselaer metabasalts, however, have undergone considerably higher degrees of alteration. The samples from Vermont (table 2) are described

Table 3
(continued)

Name	Adirondack Mts.		Zone 3		Catoctin		Catoctin		Catoctin	
Location	New York		Vermont		Pennsylvania		Virginia, N.		Virginia, S	
n , s.d.	31	s.d.	13	s.d.*	8	s.d.	7	s.d.	4	s.d.
SiO_2	50.47	2.0	48.26		51.64	0.7	50.30	1.8	50.57	1.7
TiO_2	2.78	0.5	1.89		2.54	0.2	2.68	0.8	2.35	1.1
Al_2O_3	14.48	0.9	15.48		13.76	0.4	14.94	0.3	13.56	0.4
FeO	11.50	1.1	12.79		13.76	1.1	13.51	1.8	14.00	0.8
MnO	0.16	0.0	0.19		0.23	0.0	0.26	0.8	0.24	0.0
MgO	7.18	1.4	7.05		5.84	0.9	6.34	0.6	6.20	0.9
CaO	8.37	1.7	11.14		7.91	0.7	7.12	1.3	8.32	2.3
Na_2O	3.43	0.7	2.81		3.05	0.6	4.08	0.8	3.85	1.3
K_2O	1.05	0.6	0.24		0.90	0.3	0.44	0.3	0.65	0.9
P_2O_5	0.60	0.3	0.16		0.38	0.1	0.32	0.8	0.26	0.1
Rb			21		38	10				
Ba	327	154	101		170	15	140	206		
Sr	502	159	272		168	19	160	144	193	40
Th	1.7	0.3	1.00						1.4	0.3
Zr	193	74	118		152	15	120	34	144	81
Nb	29.4	14.2	16.0		14.0	3.4				
Ni	126	46	97		90	24	37	35	75	72
Cr	188	73	173		117	38	77	49	157	185
La	30.0	6.5	11.1		11.0	1.6	24.0	20.7		
Ce	70.8	18.3	27.0		31.0	4.3				
Nd	38.0	10.9	17.0		26.0	3.6				
Sm	8.0	1.6	4.2		7.0	1.3				
Eu	2.5	0.6	1.5							
Tb	0.9	0.2	1.0							
Yb	2.0	0.3	3.3				5.0	0.0	3.0	0.3
Lu	0.3	0.0	0.5							
Y	29.5452	5.35	30		33	4.66	47	7.559	54	30.9

by Coish and others (1985) as metamorphosed to fine-grained chlorite schists, albite-epidote schists, and occasionally actinolite-epidote schists with some preserved pillow structures. Ratcliffe (1987a) described the Rensselaer basalt of New York as metamorphosed to lower greenschist facies, consisting of well to poorly foliated greenstones containing varying amounts of chlorite and epidote.

The LOIB diabase dike swarms of the southern arm are remarkably similar in their appearance in the field and in thin section. In the field they are straight and discordant with sharp contacts. In thin section they consist of plagioclase that has been partially replaced by sericite, albite, and epidote; and pyroxene that has been largely replaced by chlorite and amphibole. There is also a common presence of clusters of small grains of pyrite.

Geochemical characteristics.—Despite the highly varied degree of secondary alteration to which the LOIB suites have been subjected, the LOIB major element averages (table 2) fall within a restricted range, particularly FeOt with typical values of about 14 wt percent. Most trace element averages also share a restricted range among the LOIB suites, particularly the HFSEs. Within each suite the standard deviation calculations are typically much lower for the relatively immobile HFSEs such as TiO_2 and Zr than for the relatively mobile elements such as K_2O, Ba, and Sr consistent with the varied influence of secondary alteration processes (table 2).

TABLE 4

Chemical composition of Vendian/Paleozoic? Eastern Laurentian basalt group

Name	Caldwell		Zone 4		Drummondville		Shickshock	
Location	Quebec		Vermont		Quebec		Gaspe P.	
n , s.d.	34	s.d.*	56	s.d.*	12	s.d.	35	s.d.
SiO_2	51.32		49.42		51.65	1.6	50.70	2.4
TiO_2	0.98		1.19		0.74	0.1	1.49	0.3
Al_2O_3	14.51		15.54		14.95	1.2	14.54	1.0
FeO	11.67		10.45		9.83	2.9	11.95	1.4
MnO	0.21		0.19		0.24	0.2	0.22	0.0
MgO	7.48		7.77		6.64	1.2	7.37	1.4
CaO	10.40		12.23		11.58	2.4	10.46	2.3
Na_2O	2.47		2.84		3.89	1.0	2.87	1.2
K_2O	0.88		0.27		0.40	0.4	0.24	0.1
P_2O_5	0.09		0.09		0.07	0.0	0.16	0.0
Rb	17		11		8	8	7	2
Ba	88		33		131	65		
Sr	99		115		128	37	101	39
Th	0.14		0.60		0.04	0.02	0.42	0.2
Zr	55		78		31	9	81	17
Nb	2				4	3		0
Ni	95		156		400	20	77	19
Cr	197		378		326	27	163	83
La	1.8		4.3		0.9	0.2	5.3	1.2
Ce	4.9		12.0		3.1	0.9	13.7	3.1
Nd	3.1		8.0		4.0	1.7	10.0	2.0
Sm	1.6		2.7		1.5	0.2	3.3	0.6
Eu			1.1		0.6	0.1	1.3	0.2
Tb			0.7		0.5	0.1	0.7	0.1
Yb			3.1		2.1	0.5	3.2	0.6
Lu			0.4		0.3	0.0	0.5	0.1
Y	27		28		23	2	32	7

Major element data are recalculated to 100 percent anhydrous with ferrous and ferric iron recalculated to FeOt.
Sources of chemical data are listed in table 1.
s.d.* individual sample analyses were not published

In general, the chemical composition of the component members of the LOIB resembles OIB, generally regarded as plume derived. The compositional averages generate a cluster of lines that plots close to OIB on a silicate earth normalized (McDonough and Sun, 1995) spider diagram with elements arranged according to compatibility in oceanic basalt (Sun and McDonough, 1989). The degree of clustering is not perfect, with some scatter among the least compatible elements. However, the very tight clustering of Nd, Sm, Zr, Eu, Ti, and Tb (fig. 2) clearly relates each of the averages to each other and to OIB. In addition, each of the component members of the LOIB shares similar slopes on figure 2, with the possible exception of the Skinner Cove basalts which contain extreme and anomalous average Nb (72 ppm), La (101 ppm), and Ce (160 ppm) contents.

Shape and Size of the LOIB Plume

The LOIB component members are linked by distinct geochemical characteristics. Recognition of these characteristics makes it possible to estimate the approximate

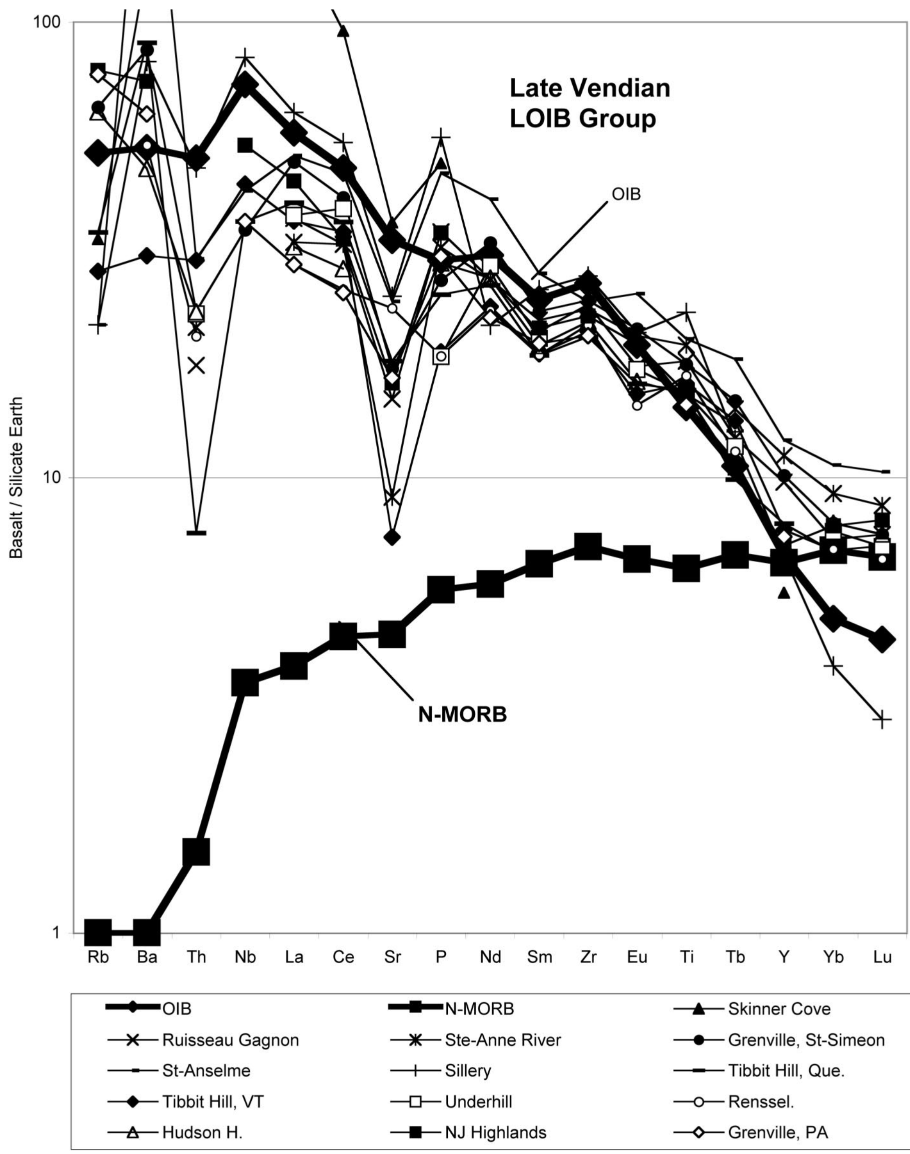

Fig. 2. Chemical composition of LOIB averages of table 2 normalized to the "Silicate Earth" of McDonough and Sun (1995) compared to the standard OIB and N-MORB of Sun and McDonough (1989). Sources of chemical data are listed in table 1.

shape of the plume related magmatic event. Titanium and zirconium are generally regarded as among the least mobile and least soluble of the HFSEs. When TiO_2 and Zr data are contoured onto a map of eastern North America (fig. 1) it becomes apparent that the most incompatible element enriched center of the LOIB is located near, but north, of Sutton Mountain, Quebec. Kumarapeli and others (1981) have determined that Sutton Mountain coincides with major positive gravity and magnetic anomalies they interpret as due largely to Tibbit Hill volcanism. Although the current surface expression of the Tibbit Hill volcanism is restricted to a narrow belt, Kumarapeli and

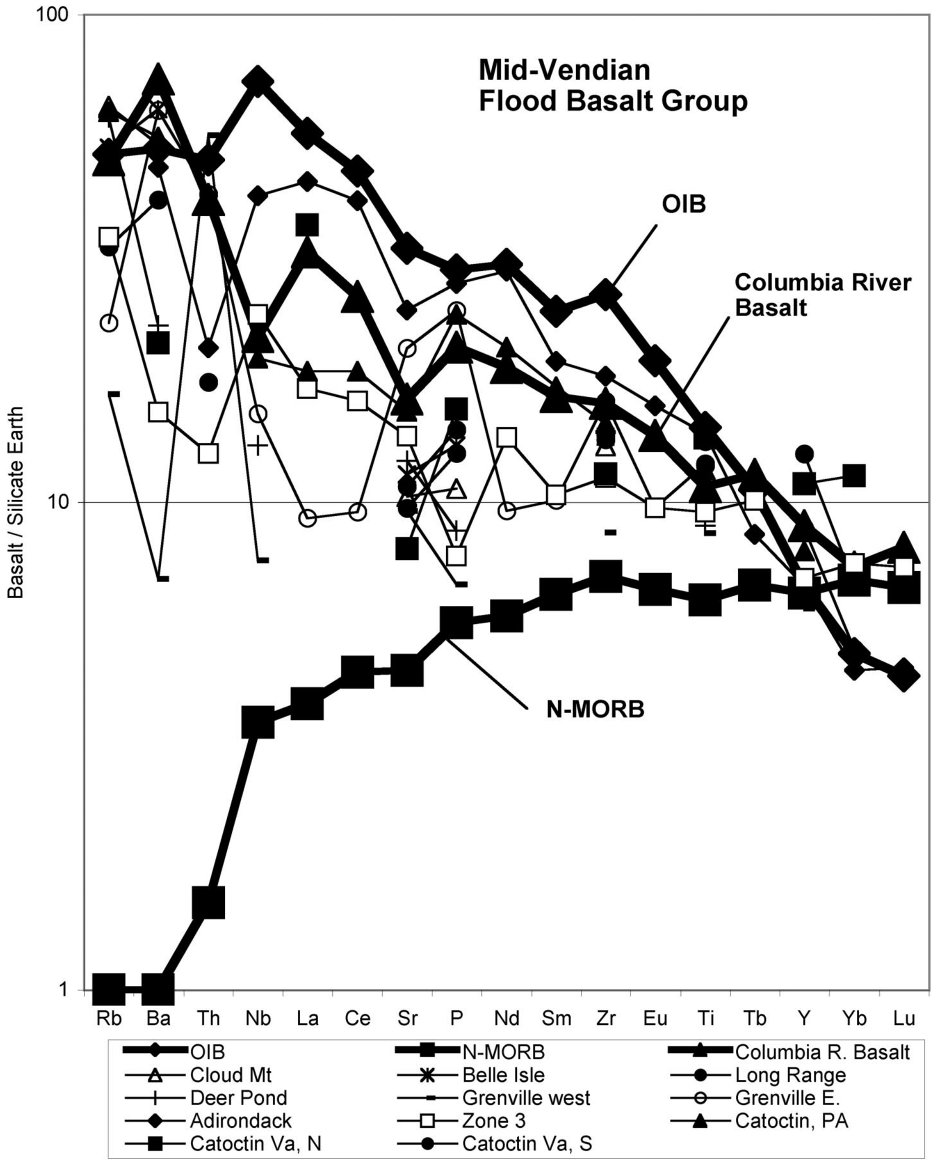

Fig. 3. Chemical composition of mid-Vendian flood basalt averages of table 3 normalized to the "Silicate Earth" of McDonough and Sun (1995) compared to the standard OIB, and N-MORB of Sun and McDonough (1989). Sources of chemical data are listed in table 1 except for average of 59 samples of Columbia River Basalt after Hooper and Hawkesworth (1993).

others (1981) conclude that their gravity and magnetic data are consistent with an 8 km thick pile of Tibbit Hill basalt that probably covered a considerable portion of eastern Canada and New England.

The shape of the contours (fig. 1) is interpreted to approximate the shape of the plume that generated the LOIB. Apparently LOIB magmatism was concentrated along the eastern margin of Laurentia generating a thin lensoid shape. Some component members of the LOIB may have been displaced westward during Appalachian thrust-

TABLE 5

Chemical composition of superplume basalts

Name	Skinner Cove		Sillery		Hiva Oa		Aniva*		Aniva + andesites**	
Location	Newfoundland		Quebec		Polynesia		Japan		Japan	
n, s.d.	7	s.d.	14	s.d.	8	s.d.	28	s.d.	36	s.d.
SiO_2	44.66	2.7	46.20	4.6	47.96	1.5	46.38	2.8	47.39	3.3
TiO_2	3.55	0.4	4.63	0.9	3.84	0.4	3.71	1.0	3.10	1.4
Al_2O_3	13.46	0.8	11.72	1.7	13.77	1.3	13.34	2.0	13.65	2.1
FeOt	12.42	1.2	13.82	3.9	11.36	0.9	12.15	2.1	11.71	2.2
MnO	0.26	0.1	0.27	0.2	0.15	0.0	0.20	0.1	0.19	0.1
MgO	9.22	2.5	8.45	2.5	8.26	3.0	7.14	2.3	7.12	2.2
CaO	12.54	2.0	10.16	3.1	9.66	0.9	10.77	3.7	10.73	3.5
Na_2O	2.37	0.5	2.83	1.6	2.94	0.4	3.83	1.3	3.84	1.1
K_2O	0.75	0.4	0.74	1.1	1.52	0.4	1.19	1.0	1.17	1.1
P_2O_5	0.76	0.1	1.16	1.8	0.54	0.1	1.30	0.7	1.09	0.8
Rb	11	6	13	11	31	15	21	20	22	20
Ba	307	72	540	519	261	65	363	319	335	301
Sr	651	113	497	310	628	45	502	168	453	202
Th			3.8	1.7	3.9	0.9	5.4	2.9	5.3	3.0
Zr	219	7	291	107	324	31	318	153	273	174
Nb	47	4	55	24	36	4	58	27	49	33
Ni	169	123	243	131	172	116	94	89	94	80
Cr	193	152	243	71						
La	75.6	3.2	41.1	18.5	34.8	3.0				
Ce	114.2	8.2	90.8	41.4	79.7	5.9				
Nd			27.2	27.1	37.9	2.8				
Sm			10.5	4.4	8.6	0.7				
Eu			3.2	1.2	2.8	0.3				
Tb			1.2	0.2						
Yb			1.7	0.5	2.0	0.2				
Lu			0.20	0.09	0.29	0.02				
Y	21	1	29	10	28	3	28	7	27	7

Major element data are recalculated to 100 percent anhydrous with total ferrous and ferric iron recalculated to FeOt.

Data sources are indicated on fig. 5 caption.

Aniva* average not including eight low-Ti andesites plotted onto fig. 5.

Aniva + andesites** includes eight low-Ti andesites plotted onto fig. 5.

ing by as much as 100 km from their original locations (Ernst and Buchan, 1997). However, most thrusting estimates, particularly southern Appalachian thrusting, are highly uncertain and probably involve less than 60 km (Alec Gates, personal communication). Since figure 1 has not been adjusted for Appalachian thrusting most contours would need to be repositioned eastward to plot on their pre-thrusting locations. On the scale of figure 1 this undetermined repositioning would not materially reconfigure the contours.

The LOIB Plume Compared to Other Mantle Plumes

Tatsumi and others (1998) have compared the chemical composition of superplume-related basalts from the Polynesian superswell with Cretaceous superplume basalts from the western Pacific. Although Polynesian superplume basalts have been characterized as HIMU basalts (high μ; $\mu = {}^{238}U/{}^{204}Pb$) by Kogiso and others (1997),

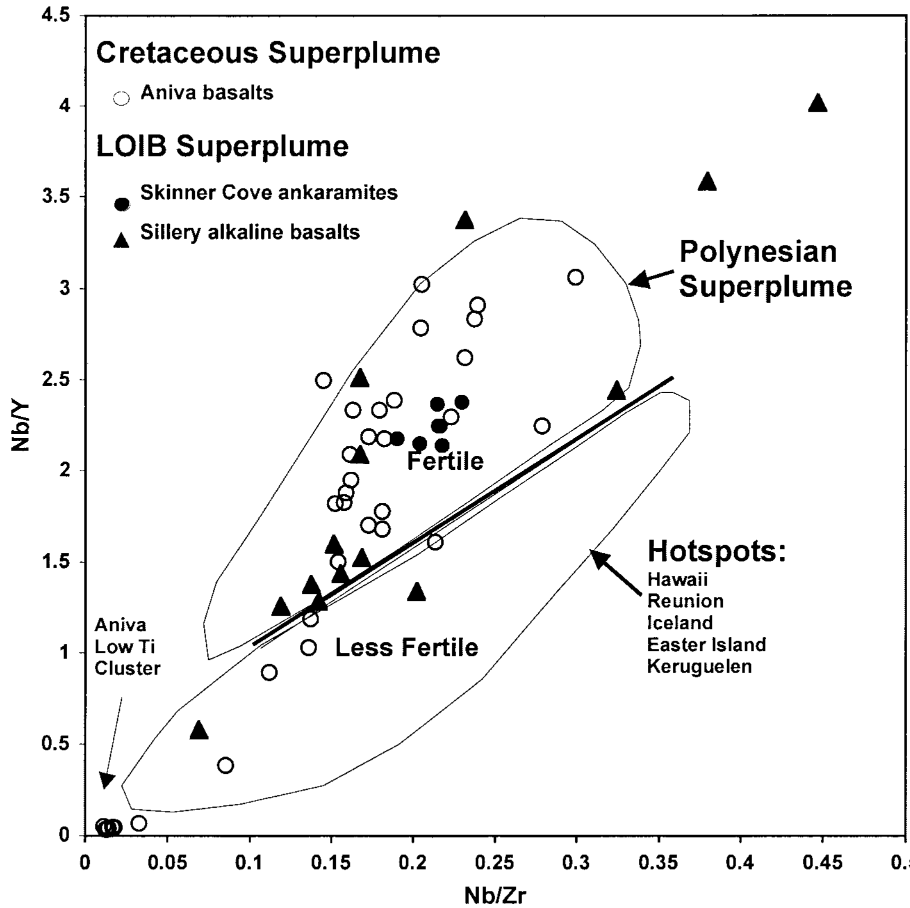

Fig. 4. The Nb, Zr, and Y data from table 5 and from an average of 6 "alkali basalts" (Vermette and others, 1993), plotted onto a modified version of a Nb/Y versus Nb/Zr diagram for hotspots and plateau lavas in Pacific, Atlantic, and Indian Oceans by Tatsumi and others (1998).

Tatsumi and others (1998) point out that Pb isotope geochemical signatures might not be applied to old, altered, and/or metamorphosed samples because of compositional changes during secondary processes. Tatsumi and others (1998) suggest, instead, that HFSE elements are a more appropriate means of comparison because they are less mobile and less subject to fractionation processes. They suggest that plots of Nb/Zr versus Nb/Y ratios are particularly useful and show that many of the Cretaceous basalts from western Pacific sites plot in the same compositional field as the Polynesian basalts of figure 4. Figure 2 indicates that Y contents are not useful in distinguishing among source regimes but are useful in providing a base line to compare other element contents such as Nb and Zr that display large contrasts. Therefore, Nb/Y and Nb/Zr ratios (fig. 4) provide accurate measures of the slopes of the lines plotted onto spider diagrams such as figure 2. Of the several Cretaceous basalts from the western Pacific, basalts from Aniva analyzed by Tatsumi and others (1998) overlap the Polynesian field (fig. 4) particularly well and provide good evidence that Aniva volcanism was part of the Cretaceous superplume event.

Similarly, the composition of basalts from the geographic center of the LOIB plot within the same field described by Tatsumi and others (1998) as the superplume field (fig. 4), although LOIB basaltic compositions, in general, become progressively less fertile at distal geographic positions. The Nb/Y and Nb/Zr ratios of 14 samples of Sillery basalt located at the LOIB plume center as analyzed by Olive and others (1997) and Vermette and others (1993) overlap the entire superplume field of figure 4. In addition, the Nb/Y and Nb/Zr ratios of 7 samples of ankaramite from the Skinner Cove suite located near the northern end of the LOIB lensoid shape (fig. 1) plot within the center of the superplume field. The Skinner Cove ankaramite flows are much less fractionated than the other Skinner Cove flows and constitute a distinct sub-suite of relatively uniform composition (low standard deviations, table 5).

The Nb/Y and Nb/Zr ratios of superplume basalts are unusually high among terrestrial basalts. Although similar levels of Nb enrichment are reached whenever alkalic magma undergoes high degrees of fractionation, another important characteristic of superplume basalts are their elevated compatible element contents (MgO, Cr, Ni) resulting in a rare combination of elevated compatible and incompatible elements. Each of the superplume basalts is rich in MgO and Ni (table 2) and probably represents primary superplume melt. Table 5 also shows a remarkable chemical similarity shared by the four superplume basalt suites. The degree of similarity is even closer if the cluster of "low-Ti samples" analyzed by Tatsumi and others (1998) (fig. 4) is removed from the Aniva average (table 5) and plotted on a spider diagram (fig. 5) generating a cluster of lines that very closely overlap. Justification for their removal is the likelihood that the low-Ti cluster is related to calk-alkaline island-arc processes genetically unrelated to the fertile Aniva samples.

The chemical composition of basalt from each of the three superplumes plotted onto figure 5 is unlike basalt from any other source. Basalt from Earth's largest continental flood basalt provinces, including each of the 401 samples from the 10 flood basalt provinces described by Puffer (2001), are less enriched in Nb at comparable MgO levels than the superplume samples plotted onto fig. 4. In addition, each of several hotspot-generated ocean island basalts including Hawaii, Reunion, Iceland, Easter Island, and Keruguelan plot in a field described by Tatsumi and others (1998) as "less fertile" than the "fertile" superplume field (fig. 4).

Kosigo and others (1997) suggest that the geochemical signature of Polynesian basalt is consistent with a source reservoir near the core-mantle boundary. They also suggest on the basis of isotopic data that the lower mantle Polynesian basalt reservoir incorporated subducted oceanic crust before ascending back to the Earth's surface as mantle plumes. The incorporation of subducted crust would explain the enrichment of Nb into the lower mantle reservoir. Nb is retained by subducted crust as partial melting and mantle metasomatism deplete subducted crust in other incompatible elements. This retention results in the negative Nb anomaly that is a characteristic of andesites and arc basalts.

THE MID-VENDIAN FLOOD BASALT GROUP

The mid-Vendian basalt group is defined on the basis of both chronological and geochemical criteria. Each of the twelve mid-Vendian rock suites of table 1 has been radiometrically dated or has been directly correlated with basaltic rocks within a 615 to 564 Ma range. In addition, each of the mid-Vendian suites is less enriched in incompatible elements than OIB. The mid-Vendian data plotted onto figure 4 generate lines that consistently fall below the OIB line, particularly Ti, Tb, and Y data. The Adirondack Dike swarm is the most enriched member of the mid-Vendian group and would plot within the LOIB cluster except for its Tb and Y data. However, the Adirondack Dike swarm has been dated at 588 Ma, K/Ar (Coish and Sinton, 1992; Isachsen and others, 1988).

The oldest members of the group are the 615 Ma Long Range dikes of Labrador and the Bell Isle basalt flows (fig. 1) that were fed from Long Range dikes located at the

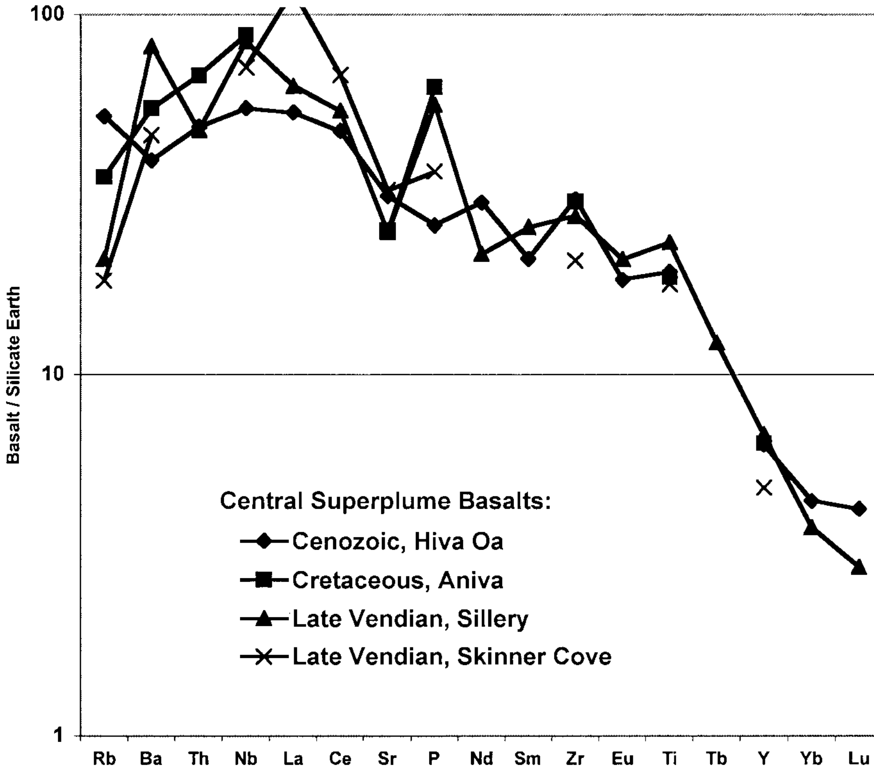

Fig. 5. Chemical composition of superplume rock suite averages of table 5 normalized to the "Silicate Earth" of McDonough and Sun (1995) compared to the standard OIB, and N-MORB of Sun and McDonough (1989). The source of chemical data: for the Cretaceous Aniva basalts of Japan is Tatsumi and others (1998) excluding volcanic rocks containing less than 4 wt percent MgO and totals less than 90 wt percent; for the Hiva Oa basalts from the Polynesian super swell or superplume is Kogiso and others (1997); for the ankaramite flows of the Skinner Cove Formation from Newfoundland is Baker (1978); and for the alkaline basalts of the Sillery Formation from Quebec is Olive and others (1997) and Vermette and others (1993).

northern end of the Central Iapetus magmatic province (Strong, 1974). The radiometric ages of the remaining members of the group progressively decrease southward toward the Catoctin flows (dated at 564 Ma, Aleinikoff and others, 1995) tempting speculation that the group may be genetically related to a hotspot under a mobile, Laurentian plate. However, some of the radiometric data pertains to an east-west oriented central zone, including the Grenville dike swarm, the Buckingham basalts, and perhaps the Adirondack dike swarm, that constitutes the western failed arm of the Sutton Mountain triple junction (fig. 1). It might, therefore, be concluded that the northern arm rifted first, followed by the western arm, and then the southern arm; however, chronological data based on granitic plutons suggest otherwise. Some granitic and layered mafic plutons that intruded into eastern Laurentia during the mid-Vendian such as the 565 Ma Sept Iles intrusion (Higgins and van Breemen, 1998) are located in the northern arm that is 615 to 602 Ma on the basis of basaltic dates (table 1). The Sept Iles pluton is located across the St-Lawrence River from the undated Shickshock basalts (fig. 1). Other mid-Vendian plutonic rocks include the Mount Rigaud syeno-granite stock dated at 564 Ma by Malka and others (1996) located north of the 588 Ma Adirondack dike swarm (fig. 1) and the Mutton Bay syenite intrusion dated at 578 Ma by Doig (1970) located across the Gulf of St. Lawrence from the 550 Ma Skinner Cove Formation (fig. 1). Therefore, the locations of the age-dated plutons together with the basaltic suites do not reveal a pattern of decreased age in any geographic direction. These granitic and layered plutonic rocks are each chemically consistent with A-type magmatism and anorogenic emplacement, and Higgins and van Breemen (1998) have proposed that the Sept Iles pluton is plume related. However, their genetic relationship to the basaltic rocks is unclear and beyond the scope of this paper.

The 615 to 564 Ma flood basalt group, therefore, represents a prolonged period of magmatism that may or may not genetically and/or chronologically overlap the LOIB event. Although LOIB magmatism is characterized by a consistent and distinct resemblance to OIB basalt there is no compositional gap separating the LOIB cluster from the less enriched flood basalt cluster. Chronologically there is also an absence of a clearly defined gap. In addition, it should be pointed out that the radiometric data (table 1) vary in precision from $+/-2$ to $+/-32$ Ma, are based on samples subjected to highly varying degrees of alteration, and were determined by a variety of procedures. For example, as pointed out by Cawood and others (2001) the 550.5 Ma age of the LOIB Skinner Cove volcanics determined on the basis of 550.5 $^{+3}/_{-4}$ Ma U/Pb determinations by McCausland and others (1997) was previously determined as 423 $+/-$ 6 Ma on the basis of K/Ar data (D. Archibald, 1973, personal communication, in Strong, 1974), as 358 $+/-$ 3.3 Ma on the basis of Ar/Ar data by Idleman (1990) and as Early Ordovician on the basis of fossils near the type locality that were reinterpreted by Williams (1975) as contained within displaced melange. The identities of the mid-Vendian flood basalt group and the late Vendian LOIB group are, therefore, determined largely on the basis of their geochemical characteristics (figs. 2 and 3), not their chronological ages.

Geologic setting.—Compared to the LOIB group, the early flood basalt and related diabase dike group is geographically more widespread and generally occur around the margins of the LOIB plume. The geologic setting of the six mid-Vendian suites composed of basalt flows is more difficult to characterize than the LOIB flows because the interbedded metasedimentary rocks have been subjected to generally higher degrees of metamorphism. However, the geologic setting is generally consistent with sub-aerial deposition.

Strong (1974) describes the Belle Isle flows of Labrador as underlain by up to 250 m of arkosic sandstone and the near-by Cloud Mountain flows of Newfoundland as underlain by about 1 m of arkosic sandstone deposited unconformably on Precambrian gneissic basement. These two flow suites make up the Lighthouse Cove Formation that chemically resembles the Long Range dikes (Strong, 1974).

Williams and others (1985) describe a narrow continuous mafic flow which they informally call the Deer Pond volcanics as occurring at the stratigraphic top of the Hughes Lake igneous complex that includes the Round Pond Granite. The Deer Pond volcanics are overlain by about 1 km of arkosic metagraywacke. The Buckingham flows of the Ottawa graben are described by Lafleur and Hogarth (1981) as massive, dark gray to almost black flows unconformably overlying high-grade Grenvillian metasedimentary rocks. The metasediments are described as reddened and friable near contacts, implying subaerial deposition. In addition, Reed and Morgan (1971) interpret the Catoctin flood basalt as sub-aerial and find it interbedded with a thick sequence of "eugeosynclinal sediments."

The geologic setting of the Hancock greenstone (metabasalt) of the Pinney Hollow Formation within "zone-3" of Coish and others (1985) is particularly difficult to characterize because of metamorphic complexities but is included in the mid-Vendian group on the basis of chemical (fig. 3) and chronological (table 1) evidence.

Petrography.—As was the case with the LOIB occurrences, the component members of the mid-Vendian group range from slightly to highly altered or metamorphosed. In general, the northern and western occurrences, with some exceptions, are only slightly altered; however the central and southern occurrences are highly altered, particularly metamorphic alteration.

The least metamorphosed member is the Grenville Dike Swarm. These mid-Vendian dikes intruded into Grenville rock and are described by St. Seymour and Kumarapeli (1995) as consisting of pyroxene (predominately zoned augite), plagioclase (predominately An65), serpentinitized olivine, titanomagnetite, and ilmenite. The dikes and flows of northwestern Newfoundland and the Adirondack dikes have also undergone only slight metamorphic alteration. Strong (1974) describes the Newfoundland dikes as generally fresh, largely consisting of augite, plagioclase, and serpentine pseudomorphs after olivine, but some of the augite is partially altered to actinolite, and some plagioclase is sausseuritized. Coish and Sinton (1992) describe the Adirondack dikes as generally fine-grained altered diabase containing phenocrysts of plagioclase in a groundmass of finer-grained plagioclase and partially chloritized pyroxene. Only 5 to 10 percent of the Adirondack dike plagioclase is altered to sericite, and some olivine cores have escaped alteration. In addition, the Cloud Mountain basalts of Newfoundland have undergone low degrees of metamorphism, although Strong (1974) and Strong and Williams (1972) indicate that chlorite and actinolite have slightly replaced some augite, and the plagioclase is generally saussuritized. The basalt flows of Belle Isle are petrographically similar to the Cloud Mountain basalts but have undergone substantially more alteration (Strong and Williams, 1972).

The Deer Pond basalt of western Newfoundland is described by Williams and others (1985) as a narrow continuous flow at the stratigraphic top of the complex that has been metamorphosed into biotite-chlorite schist. Lafleur and Hogarth (1981) also describe high degrees of alteration throughout exposures of Buckingham basalt, with sericitized plagioclase and chloritized pyroxene and fractures coated with carbonate, quartz, epidote, and riebeckite; however, the basalt does not show planar fabric or metamorphic effects and retains a fine-grained amygdaloidal texture.

Even higher degrees of alteration characterize the Vermont and southern occurrences. There are no relic igneous textures preserved in the Zone 3-Hancock greenstone of the Pinney Hollow Formation (Coish and others, 1985). Assuming the Hancock is a metabasalt flow component and not intrusive into (younger than) the Pinney Hollow, its age would be comparable to the 571 Ma U-Pb (zircon) age of a metafelsite gneiss component of the Pinney Hollow Formation dated by Walsh and Aleinikoff (1999) and is, therefore, presumed to be a member of the mid-Vendian group.

Reed and Morgan (1971) provide evidence that most of the alteration of Catoctin basalt is the product of greenschist facies metamorphism. However, south of Pennsylvania the degree of metamorphism increases from greenschist to amphibolite facies, and it becomes increasingly difficult to distinguish metabasalts from volcaniclastics (Wang and Glover, 1997).

Geochemical characteristics.—Each member of the mid-Vendian group is quartz-tholeiitic and geochemically resembles some large continental flood basalt provinces. They are particularly similar to continental flood basalt provinces that involved considerable input from a subcontinental lithospheric mantle source together with input from a mantle plume source such as the Columbia River Basalt (Hooper, 1997; Hooper and Hawkesworth, 1993). The group, in general, chemically resembles an average of 59 samples from the main sequence of Columbia River basalt (fig. 3). Hooper (1997) provides compelling evidence that the Columbia River flood basalt resulted from the impingement of the Yellowstone hotspot on subcontinental lithosphere.

Similar proposals have been applied to several members of the mid-Vendian group. St. Seymour and Kumarapeli (1995), in particular, suggest a mixed plume-subcontinental source for the Grenville dike swarm. They observed that the chemistry of the Grenville dike swarm becomes increasingly plume-like as it approaches the Sutton Mountain triple junction. They conclude that the principle source was a depleted entrained mantle and that the minor source was an enriched discoid plume head located near Sutton Mountain. The composition of the eastern portion of the swarm is more enriched in HFSEs with average TiO_2 and Zr contents increasing from 1.69 wt percent and 100 ppm (west half, table 1) to 2.37 wt percent and 169 ppm (east half). This observation is consistent with a slowly rising plume that at intermediate levels was mixed with more subcontinental lithospheric derived melt at distal (western Grenville) positions than at central or at shallow positions closer to the epicenter of the plume near the triple junction. Apparently the failed western arm of the triple junction did not transmit the most enriched portion of the plume.

The Adirondack dike swarm is about the same age as the Grenville dike swarm but is still closer to the triple junction and is even more enriched (fig. 3) than eastern Grenville dikes, consistent with the observations of St. Seymour and Kumarapeli (1995). Coish and Sinton (1992) also suggest a plume source for the Adirondack dike swarm partially on the basis of its similarity to some of the plume related flows of the East African Rift System.

As was the case with the LOIB group, the TiO_2 and Zr contents of the mid-Vendian flood basalt suites can be contoured. The contours around the mid-Vendian locations (the dashed lines of fig. 1A and B) generate a similar pattern around the Sutton Mountain triple junction but show lower degrees of HFSE enrichment and represent a wider geographic area. The concentric pattern of two sets of contours around the same point also suggests a genetic relationship of the early group with the late group.

VENDIAN/EARLY PALEOZOIC? GROUP

At least four basaltic rock suites of questionable Vendian to early Paleozoic age (table 1) are found within the boundaries of the Central Iapetan magmatic province: (1) Zone 4 of Vermont, (2) the Shickshock greenschists, (3) the Caldwell basalts, and (4) the subalkaline basalts of Drummondville (fig. 1). None of these suites has been radiometrically dated, and each is highly altered. In addition, the chemical composition of each of the four suites resembles N-MORB (fig. 6) in distinct contrast with LOIB plume chemistry, suggesting a completely independent source and tectonic setting. However, to the extent that they may be genetically or chronologically related to the LOIB they need to be examined.

There are some problems with each of the four members of this questionably late group that make them difficult to characterize. To varying degrees they have been subjected to hydrothermal alteration or metamorphism that has largely obscured or obliterated their igneous texture and may have altered their chemical compositions. For example, there are no relic igneous textures preserved in the Zone 4 greenschists of the Ottauquechee and Stowe Formations (Coish and others, 1991). Stratigraphic criteria presented by Coish and others (1991) and Stanley and Ratcliffe (1985) indicate that rocks of Zone 4 are older than 470 Ma Taconic metamorphism but perhaps younger, by an undetermined amount, than the Hancock greenschist that Coish and others (1991) correlate with the 571 Ma Pinney Hollow Formation.

There is even less certainty regarding the age of the Shickshock greenschists. Lux (1986) suggests that the Shickshock was transported westward from the Dunnage Zone together with the 456 Ma Mount Albert ophiolite complex into the Humber Zone. However Camiré and others (1995) interpret the Shickshock as erupted in the

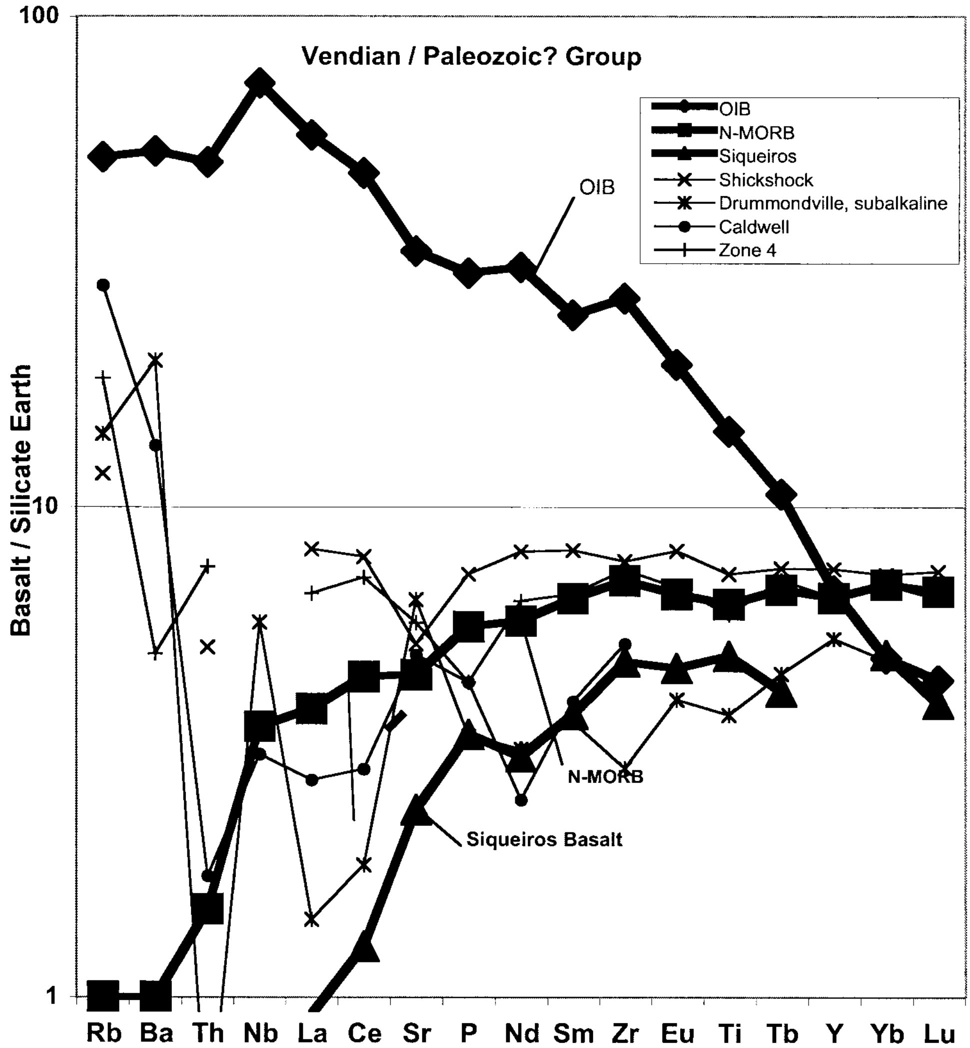

Fig. 6. Chemical composition of rock suite averages of questionable Vendian to early Paleozoic age (table 4) from sources listed in table 1 normalized to the "Silicate Earth" of McDonough and Sun (1995) compared to the standard OIB and N-MORB of Sun and McDonough (1989) and an average of 8 picritic basalts extruded from the Siqueiros transform fault (Perfit and others, 1996).

Humber Zone during the rifting that led to the opening of the Iapetus (about 615-550 Ma). Igneous amygdaloidal textures and pillowed structures are preserved in the Shickshock suggesting marine, perhaps early Iapetan MORB eruptions, although the flows are found with metasediments derived from a continental (Laurentian) source (Camire and others, 1993).

Bedard and Stevenson (1999) use a similar association of Caldwell metabasalt with sediments that Cousineau (1990) interprets as derived from a cratonic provenance (meta-feldspathic-wackes) as evidence of a rift relationship and, therefore, Vendian age. They correlate the Caldwell with the Shickshock and other lithologies in the Hadrynian to Early Cambrian External Nappe Domain in agreement with St. Julien and Hubert (1975). However, evidence of an early Paleozoic age for the Caldwell includes its intimate association with the early Paleozoic Thetford Mines ophiolite dated as 478 Ma (U/Pb zircon) by Dunning and others (1986), although Bedard and Stevenson (1999) interpret this intimate association as tectonic interslivering. Additional evidence of an early Paleozoic age is the chemical similarity of the Caldwell to the "subalkaline" flows of the Drummondville Olistostrome (table 4), generally agreed to be Middle Ordovician (Pinet and Tremblay, 1995; St. Julien and Hubert, 1975). Some of the unusual chemical characteristics of the Caldwell basalts shared by the basalts of the Drummondville Olisostrome exposed about 50 km to the northwest (fig. 1) are extremely low La, Ce, Nd, and Sm contents (table 4, fig. 6). With the exception of contrasting Al_2O_3 levels, the Caldwell basalts also compare closely to the chemical composition of the EAS basalts of the Ascot Complex (Hynes, 1980), exposed in and near Sherbrooke in the Dunnage Zone near Sutton Mountain (fig. 1), which Pinet and Tremblay (1995) interpret as part of an Ordovician arc system.

The Zone 4, Shickshock, and Caldwell metabasalts, therefore, may be younger than the LOIB, although there are no direct age data available. If they are Neoproterozoic it is unlikely that they are genetically related to the LOIB. However, an association of Caldwell and Shickshock flows with continental margin sediment (Bedard and Stevenson, 1999) may still be consistent with a MORB composition and a post-LOIB plume stratigraphy if they, Zone 4 of Vermont, and the subalkaline basalts of Drummondville were extruded out of transform faults intersecting the trailing edge of a Laurentian continental margin during the opening of the Iapetus Ocean. Of all the various MORB magma types, perhaps the closest match to the uncommon chemistry of the Caldwell and Drumondville basalts is the picritic basalt that extruded out of the Siqueiros transform fault of the East Pacific Rise (Perfit and others, 1996) as plotted onto figure 6.

Conclusions are difficult, but until some of the uncertainties are resolved, each of the four members of the questionably early Paleozoic group are interpreted as post-LOIB magmatism.

DATA ANOMALIES AND EXCLUSIONS

Although there are probably countless unanalyzed Appalachian amphibolites and greenstones that may or may not be genetically related to the LOIB plume, the search of the literature on which this report is based, in addition to the new analytical data, has found no compelling distortion of the general trend of incompatible element enrichment in LOIB basaltic rock or in mid-Vendian flood basalts as the Sutton Mountain triple junction or the area just north of it is approached (fig. 1). However, the data of tables 2 to 5 plotted onto figure 1 excludes data from three sources: (1) some highly fractionated Catoctin metabasalt, (2) some highly altered Tibbit Hill metabasalt, and (3) a "transitional" basalt suite from the Drummondville area.

Catoctin exclusions.—A few occurrences of titanium-enriched metabasalt are found in southern Pennsylvania among float samples analyzed for titanium and some trace elements by Smith and others (1991) and Smith and Barns (1994). In particular, five float samples containing 3.71 to 4.57 percent TiO_2 were found by Smith and others (1991) along the eastern edge of the South Mountain anticlinorium of south-central Pennsylvania. They interpret the samples as Catoctin metabasalt and refer to them as the "Conewago Narrows" metabasalt series. New chemical analyses of two additional float samples of metabasalt found near the Conewago Narrows sample sites of Smith and others (1991) closely compare to their published trace element composition but suggest a very high degree of fractionation compared to more typical Catoctin samples including those collected at stops 3 and 4 sites of Smith and others (1991) that are averaged in table 3. The TiO_2, MgO, Ni, and Cr contents of the two new Conewago Narrows samples average 3.9 and 4.2 percent and 6 and 10 ppm, respectively, in contrast to the more typical average of 2.5 and 5.8 percent and 90 and 117 ppm of stops

3 and 4 samples (table 3) and other typical Catoctin basalt samples from several locations described by Smith and others (1991), Reed and Morgan (1971), and Wang and Glover (1997). The highly fractionated composition of the Conewago Narrows samples are, therefore, not representative of Catoctin basalt but instead closely resemble some segregation sheets commonly found in flood basalts that are the product of post eruptive, in-situ fractionation (Puffer and Volkert, 2001).

Tibbit Hill exclusions.—As previously described, alteration has complicated interpretation of some of the rock suites near the center of the LOIB. In most cases variations in the degree of alteration among samples in LOIB suites are "averaged out" and lead to meaningful data (table 2). However, the most highly altered of all the Vendian suites is the LOIB Tibbit Hill metabasalt suite from the Sutton Mountain area where blueschist facies metamorphism has obliterated all igneous texture and left an albite-chlorite-epidote-amphibole assemblage with some stilpnomelane (Trzcienski, 1976). The resulting rock has undergone highly varied degrees of hydration and metasomatism with LOI ranging from 1.38 to 8.45 and MgO ranging from 0.99 to 9.49 wt percent. To avoid bias, a sample screen has not been used for any of the other Vendian suites averaged in tables 2 to 4 but it is probably reasonable to exclude basalt samples that have undergone more than 8 percent hydration and samples containing less than 0.02 percent K_2O or less than 2.5 percent MgO. Exclusion of such samples from the database of Abdel-Rahman and Kumarapeli (1999) leaves three Tibbit Hill samples (table 2) that are chemically similar to the average of nine Tibbit Hill samples from Vermont (Coish and others, 1985).

Drummondville exclusions.—A suite of chemically and petrographically diverse samples of uncertain stratigraphic position from the Drummondville area (fig. 1) has been described as "transitional" by Vermett and others (1993) and Olive and others (1997). These transitional basalts and dikes are found in both the Middle Ordovician Olistostrome and in the underlying Sillery Group that was deposited over an extended time range from Vendian, on the basis of its correlation to the Tibbit Hill flows (Olive and others, 1997), to as young as Middle Ordovician at its upper contact with the Olistostrome (St-Julien and Hubert, 1975; Pinet and Tremblay, 1995). These transitional basalts and dikes contain 1.3 to 3.4 percent TiO_2 and 75 to 420 ppm Zr. As a group they defy characterization, and an average would be meaningless. However, they are typically located along fault zones, and, as may have been the case with the Caldwell flows, (Bedard and Stevenson, 1999), some of the transitional basalt samples may have been thrust into tectonic juxtaposition with younger Ordovician strata.

NEOPROTEROZOIC RIFT-DRIFT MODELING

The separation of the Central Iapetian basaltic rock suites into a mid-Vendian (615-564 Ma) flood basalt group and a late Vendian (554-550 Ma) LOIB superplume group can be interpreted tectonically either of two ways: (1) a single prolonged superplume event, and (2) mid-Vendian South Polar flood basalt volcanism followed by late Vendian near equatorial superplume magmatism.

A single prolonged superplume event.—With the exception of the 615 Ma date for the Long Range dikes of southeast Labrador the radiometric dates pertaining to Vendian basaltic rocks range from 602 to 550 Ma (table 1). This approx 50 Ma range is comparable to the life cycle of two superplume events described by Larson (1991A, B); mid-Cretaceous (124-83 Ma) and Pennsylvania-Permian (323-248 Ma) events. An approx 50 Ma time-span separating the early stages of deep mantle plume related magmatism from the shallow crustal emanations of a plume head is also consistent with the prolonged magmatism of other large plume related occurrences of continental flood basalt (Johnston and Thorkelson (2000); Puffer, 2001).

Although there is a 10 Ma gap in the radiometric data separating the early group from the late group, difficulties interpreting intra-lab data based on a variety of techniques, together with problems pertaining to high degrees of sample alteration may render the 10 Ma gap meaningless. If, instead there was a smooth transition from early to late basalt the distribution of occurrences around a single central point suggests that the Laurentian plate was approximately stationary while a single rising plume was penetrating it. A single plume event would be consistent with the approximate geographic co-existence of: (1) a major gravity and magnetic anomaly at Sutton Mountain due to the 8 km thick pile of Tibbit Hill volcanism, (2) the geographic center and the compositionally most enriched portion of the late Vendian LOIB, (3) the convergent point (a triple junction) of three major dike swarms (the Long Range dikes; the Adirondack-Grenville dikes, and the Hudson Highlands-New Jersey Highlands-Grenville, Pennsylvania dikes), and (4) the geographic center of the mid-Vendian flood basalt group.

A single event would also be consistent with the gradual change in basalt composition from early and widespread flood basalt magmatism involving considerable input from a subcontinental lithospheric source to late, less widespread magmatism from a superplume head that had finally penetrated to shallow levels. In addition, a single prolonged magmatic event would allow sufficient time for prolonged Pannotian plate stretching, sedimentation, and rifting (Soper, 1994) culminating in the final separation of Laurentia from Gondwana at approx 550 Ma. No evidence of a plume tract would be retained, because the plume head would be located at the trailing edge of both Laurentia and Gondwana.

If so, Laurentia was an integral part of Pannotia throughout most of the Vendian and was presumably located near the South Pole as suggested by most pre-breakup paleomagnetic based reconstructions including Soper (1994), Dalziel and others (1994), and Dalziel (1997). A late Vendian LOIB superplume, therefore, may have played an integral role in the break-up of Pannotia, the opening of the Iapetus Ocean, and the subsequent rapid northern drift of Laurentia.

However, the paleomagnetic and radiometric data of McCausland and Hodych (1998) suggest that the Skinner Cove Formation occupied an approx 19° south latitude position during its 550.5 +3/−2 Ma. extrusion. Recent paleogeographic reconstructions by Cawood and others (2001), therefore, suggest that the Skinner Cove volcanism occurred after Laurentia separated from Gondwana and not until Laurentia drifted to a near equatorial position.

Two independent magmatic events.—Cawood and others (2001) propose two independent magmatic events: (1) 570 Ma rift related magmatism culminating in the separation of Laurentia from Gondwana at South Polar latitudes, and (2) a second cycle of magmatism at 550 Ma associated with further rifting of Laurentia at equatorial latitudes. Their paleogeographic reconstruction rests largely on the 19° +/− 9° south paleolatitude position of 550 Ma Skinner Cove volcanism determined by McCausland and Hodych (1998) which forces considerable displacement from the South Polar position of Laurentia determined in part by the 564 Ma age of Catoctin volcanism (Aleinkoff and others, 1995) and paleomagnetic data pertaining to Catoctin volcanism determined by Meert and others (1994).

Recognition of a superplume event that includes Skinner Cove volcanism does not provide independent evidence precluding the reconstruction proposed by Cawood and others (2001). However, a two independent magmatic event model is difficult to reconcile with at least five observations: (1) A 564 to 550 Ma time span covering at least 7000 km of drifting equates to a rate of at least 50 cm per yr which may be unreasonable; (2) Laurentia would have drifted directly toward the 550 Ma superplume, although large plume heads are generally located at spreading centers; (3) The epicenter of the 550 Ma magmatic event would be located at approximately the same location as an independent 570 Ma magmatic event which would be an unlikely coincidence; (4) As indicated by Cawood and others (2001), a passive margin depositional cycle associated with an opening of the Iapetus at 570 Ma has not been recognized along the Laurentian margin; and (5) Although the paleogeographic model of Cawood and others (2001) calls for the drifting of northern Laurentia across a plume associated with Skinner Cove volcanism, there is no evidence of a late Neoproterozoic hotspot tract across northern Laurentia parallel to the trajectory of proposed plate movement.

The McCausland and Hodych (1998) paleomagnetic data are tilt corrected; however, paleomagnetic technology cannot correct for complex post-magnetization folding or rotation unless the extent of such folding and rotation is known. Unfortunately the distinct possibility exists that the Humber Arm Allochton containing the Skinner Cove basalt may have rotated by an unknown amount during Paleozoic thrusting and transpression. The uniform paleomagnetic data collected by McCausland and Hodych (1998) at widely spaced sample sites indicate that the allochton containing the Skinner Cove volcanics remained rigid during thrusting, but it may or may not have rotated.

Still another possibility, although just as speculative, is the interpretation made by Baker (1979) that Skinner Cove volcanics were extruded from an oceanic island or seamount. An equatorial 550 Ma Skinner Cove seamount may, therefore, have been accreted onto Laurentia after Laurentia drifted from its near South Polar breakup position.

However, Cawood and others (2001) also propose that the 550 Ma magmatic event may have been plume related and that it coincided with continued breakup of Laurentia. Terranes that separated from eastern Laurentian may have included the Argentine Precordillera, the Oaxacon terrane, and the Dashwoods block (Cawood and others, 2001). Perhaps the tectonic significance of the LOIB superplume was confined to these late Vendian terrane separations. Nevertheless, there is general agreement that Earth's environment and biodiversity began to change rapidly toward the end of the Neoproterozoic.

ENVIRONMENTAL CONSEQUENCES

Although major volcanic events are commonly associated with environmental hardship and even mass extinction, the LOIB event correlates with the beginning of a major expansion in the diversity and quantity of marine life during the early Cambrian. Larson's (1991b) study of the geological consequences of superplumes does not extend as far as the Neoproterozoic largely because of a lack of good data on the magnetic field reversal process he uses to identify superplume events. However, the two superplume events that he has highlighted occurred during the mid-Cretaceous (124-83 Ma) and the Pennsylvanian-Permian (323-248 Ma). The mid Cretaceous superplume event has been particularly well characterized (Caldeira and Rampino, 1991; Larson, 1991a, b; and Tatsumi and others, 1998) and correlates with global warming, rising sealevels, and mantle outgassing, particularly carbon dioxide and nutrients. Both of the superplumes described by Larson (1991a, b) occurred over an extended period of time, comparable to the 615 to 550 Ma range measured for the LOIB, and were also associated with a major increase in the growth rate and deposition of marine life, comparable to that of the late Vendian to early Cambrian. In addition, both the Mesozoic and Paleozoic superplumes correlate with rapid increases in convection in the outer core and with a rapid increase in seafloor spreading rates as was probably also the case with the early Cambrian (Gurnis and Torsvik, 1994; Soper, 1994; Dalziel, 1997; Scotese, C. R., 1997).

Conclusions

1. The late Neoproterozoic basaltic rock formations of eastern Laurentia fit into two major geochemical groupings: one that chemically resembles ocean island basalt (the LOIB), and another that resembles some plume related continental flood basalts such as the Columbia River basalt. A third group of questionable age resembles mid-ocean-ridge basalt (N-MORB).
2. The LOIB group is about 554 to 550 Ma, the flood basalt group is about 615 to 564 Ma, and the N-MORB group may be early Paleozoic.
3. The geographic center of the LOIB group is located near: (1) a major gravity and magnetic anomaly at Sutton Mountain Quebec, (2) the geographic center of the earlier group of flood basalts, and (3) the triple junction of the Central Iapetus magmatic event defined by convergence of the strikes of several Neoproterozoic dike swarms.
4. The center of the LOIB group is chemically the same as rare superplume basalt.
5. The LOIB superplume event may have coincided with the break-up of Pannotia and the beginning of the rapid northward drift of Laurentia; or it may have coincided with subsequent rifting of a previously separated Laurentia at an equatorial geographic position.
6. The LOIB chronologically coincides with a major expansion of biological diversity, which is a characteristic of superplume events.

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