ABDEL-FATTAH M. ABDEL-RAHMAN* and P. STEPHEN KUMARAPELI**

ABSTRACT. The Late NeoProterozoic metavolcanic Tibbit Hill Formation (THF) covers a large crustal segment exposed along a belt about 250 km long in the Appalachian fold belt (Quebec-Vermont). It is predominantly basaltic in composition but contains a minor component of felsic and intermediate alkaline volcanic lithologies.

Geochemically, the Tibbit Hill Formation forms a continuum in composition and exhibits a wide range of SiO$_2$ (44-76 wt. percent), covering the entire spectrum from alkali basalt to trachyte and comendite. This mildly alkaline suite is relatively enriched in incompatible elements and exhibits a wide range of Zr (138-1493 ppm), Nb (15-139 ppm), and Y (18-185 ppm) concentrations, among other elements. The concentrations of the HFSE and the REE gradually increase toward the more evolved lithologies. The chondrite normalized REE patterns are fractionated (LREE-enriched over HREE), parallel to subparallel, and generally uniform but with negative Eu-anomalies developed in the more felsic varieties. These geochemical features underline the comagmatic nature of the entire suite and are consistent with a fractionated basalt to comendite suites. The incompatible element profiles suggest that most of these elements including Nb, Zr, Ti, Y, and the REE have not been affected by metamorphism, as they remained largely intact within the THF rocks.

Chemical features of the mafic rocks are typical of within-plate basalts and suggest that their melts were derived from a fertile or plume-related mantle source. Chemical features of the felsic and intermediate rocks are typical of anorogenic A1 type suites, related to hotspots, mantle plumes, or continental rift zones. This is consistent with the regional geological context with the volcanism, associated with an Iapetan RRR triple junction, occurring shortly before the onset of seafloor spreading.

Geochemical modelling shows that the THF basaltic magma was produced by a very small degree of batch partial melting ($F = 2.5$ percent) of a garnet-bearing primitive mantle source (garnet lherzolite). A final basaltic melt segregation depth is estimated at 80 to 100 km. Melting probably occurred within the thermal anomaly of a rising mantle plume beneath the Sutton Mountains triple junction (near the Quebec-Maine border). Fractionation of THF basaltic magma produced minor trachytic and comenditic magmas. The volcanic assemblage of the Afar rift (for example, Boina centre) appears to represent a modern analogue to the THF volcanic suite.

INTRODUCTION

Varially altered, metamorphosed, and deformed volcanic assemblages, thought to be related to Late NeoProterozoic continental rifting (Bond, Nickeson, and Kominz, 1984), have been identified at several localities on the western flank of the Appalachians (Aleinikoff and others, 1995). Trans-Atlantic correlatives are probably represented by volcanic piles such as the Tayvallich volcanics in the Scottish Dalradians (Graham and Bradbury, 1981; Halliday and others, 1989). Of all these volcanic suites, the one that makes up the Tibbit Hill Formation (THF), exposed along a belt about 250 km long in the Appalachian Humber Zone of southeastern Quebec and northern Vermont (fig. 1), is in some ways unique. First, its age of about 555 to 560 Ma (Kumarapeli and others, 1989)
makes it the youngest of the volcanic sequences. This has led to the suggestion that the Tibbit Hill volcanism took place just before the onset of seafloor spreading and not during rift initiation some 35 Ma earlier (Kamo, Krogh, and Kumarapeli, 1995). Secondly, it is the clearest example of eruption at an RRR (rift-rift-rift) triple junction (the Sutton Mountains triple junction) in a setting similar to that of the Afar triangle (Kumarapeli, Goodacre, and Thomas, 1981). The rifting event took place as a prelude to the opening of the Iapetus ocean. Faill (1997) argues that the name Iapetus for this ocean is inconsistent with original definitions and that it should be called Theia. However, we use the name Iapetus in this paper with the understanding that it refers to the Paleozoic ocean off the “east” margin of Laurentia.

Fig. 1. Map showing the surface and subsurface extent of the Tibbit Hill Formation. Also shown are: (A) probable location of and tectonic-magmatic features (such as the Ottawa Graben, Grenville-, and Adirondack dike swarms) related to the Sutton Mountains triple junction, and (B) boundaries of the Appalachian fold belt, St. Lawrence Platform, and Canadian Shield in the map area. Inset: location map. Sources: Kumarapeli (1985), Coish and others (1985), Kumarapeli (1993), St. Seymour and Kumarapeli (1995).
The THF is predominantly composed of basalts. Previous geochemical studies of the basalts were restricted mainly to two widely separated segments of the volcanic belt (fig. 1): one in Vermont (Coish and others, 1985) and the other in the Richmond area of Quebec (Pintson, Kumarapeli, and Morency, 1985; Pintson, 1986). These studies show the effect of metamorphism and alteration on the incompatible elements was minimal. The presence of comenditic rocks in the THF of the Waterloo area (fig. 1) suggested that the Tibbit Hill volcanic suite is bimodal (Kumarapeli and others, 1989). However, our studies show that the THF also contains a minor component of intermediate lithologies (see below).

New chemical data have been obtained for 18 samples of the recently recognized intermediate lithologies of the THF and for 10 basaltic samples, all from the Richmond and Sutton areas in Quebec (fig. 1). Additional data on basalts from Vermont and Richmond have been taken from Coish and others (1985) and Pintson (1986), respectively. Data for the felsic members of the THF are taken from the only available study of these rocks (10 analyses from the Waterloo area in Quebec, Kumarapeli and others, 1989). Samples for which the concentrations of major and trace elements are available have been used in this investigation. Our aim is to (A) present the geochemistry of the Tibbit Hill mafic to felsic volcanic assemblage based on a larger data set from various parts of the entire volcanic shield; (B) propose a model for the origin of the Tibbit Hill magma, and investigate its possible connection to mantle plumes, (C) present a mechanism for the formation of the observed spectrum of lithologies, (D) further investigate the mobility of elements in response to the metamorphic episode that has affected the THF basaltic rocks, (E) compare the characteristics of volcanic products at the about 560 Ma Sutton Mountains triple junction with those at a more recent one, namely the Afar triple junction, and (F) discuss the relationship between the THF volcanic rocks, the Grenville dike swarm, and the Adirondack dike swarm.

The Tibbit Hill Formation

The THF occurs at or near the exposed base of the rift facies volcanic-sedimentary wedge that formed on the Grenvillian (approx. 1 Ga) rocks of the rifted margin of Laurentia. In Quebec, the rift facies rocks comprise the Lower Oak Hill Group, and the THF, whose base is not exposed, is the lowest recognized formation. No fossils have been found in the Lower Oak Hill Group, but Early Cambrian fossils have been recorded from the overlying Gilman Formation of the Upper Oak Hill Group (Fritz and Yochelson, 1988). Comenditic rocks in the Waterloo area have been dated (U-Pb zircon) at 554 ± 4/° 2 Ma (Kumarapeli and others, 1989), but the mafic rocks may have begun forming around 560 Ma. It should be noted that the only known rift-related igneous event of regional significance older than the Tibbit Hill volcanism is the emplacement of alkalic-carbonatitic complexes along the Ottawa and Saguenay grabens in eastern Canada with an age of 565 Ma (K-Ar age, Gittins, MacIntyre, and York, 1967; Doig and Barton, 1968).

In Vermont siliciclastic metasediments, including conglomeratic units of the Pinnacle Formation (Camels Hump Group), make up the basal rocks of the rift facies sequence; the Tibbit Hill metavolcanic suite is a member of this formation. The relatively narrow (less than 10 km) belt of THF outcrop areas shown in figure 1 represents inliers of the THF exposed at structural culminations of a major anticlinal axis. That these seemingly minor outcrop areas are merely the surface expression of a large volcanic mass, about 250 km long, up to 45 km wide and up to 8 km thick, has been demonstrated by analysis of the associated gravity and magnetic anomalies (Kumarapeli, Goodacre, and Thomas, 1981). The triangular-shaped area which represents the subsurface extension of the Tibbit Hill volcanic mass occurs in the apical area of the Sutton
Mountains salient (fig. 1) which is a prominent arcuate feature of the Appalachian fold belt. Taconian (Early-Middle Ordovician) thrusting is thought to have transported the volcanic mass and the associated sediments cratonward from their initial setting over the triple junction (fig. 1; Kumarapeli, 1993).

The volcanic stratigraphy is not clear in any of the areas studied which is not entirely unexpected because of the complex deformation and alteration of the rocks. However, amygdules are present and are locally abundant. Also, pillow structures, although rare, have been reported (Dennis, 1964; Cady, 1969). Thin, discontinuous, phyllitic layers represent sediment intercalations.

The Tibbit Hill felsic rocks occur mostly in one principal band (about 15 km long and up to 2.5 km wide) in the Waterloo area (fig. 1; Kumarapeli and others, 1989). These felsic rocks are flanked on all sides by basaltic rocks. The trachytic rocks are known from two sectors of the THF: one in the Richmond area and the other in the Sutton area. They occur within the basaltic rocks as deformed and metamorphosed remnants of thin (commonly <1m thick) flows and dike-like igneous bodies. The largest trachytic body occurs about 5 km north of Sutton (fig. 1) and is mappable as a sinuous band about 1 km long and 50 m wide. Field relations suggest that the trachytic bodies were initially tabular. The fact that some of them contain large proportions of amygdules suggests that they may have been lava flows and hence a part of the volcanic sequence.

**PETROGRAPHIC DESCRIPTIONS**

The Tibbit Hill mafic and felsic metavolcanic rocks have been described in detail by previous investigators (metabasalts: Booth, 1950; Christman, 1959; Osberg, 1965; Clark and Eakins, 1968; Pieratti, 1976; Coish and others, 1985; Pintson, Kumarapeli, and Morency, 1985; Pintson, 1986; metacomendites: Kumarapeli and others, 1989). Therefore, only brief generalized descriptions of these rocks are given. Since the intermediate metavolcanic rocks have not been described by other authors, they are treated in greater detail.

**Metabasalts**.—Mafic volcanic rocks of the THF are represented by greenschists, with a typical mineral assemblage of albite–chlorite–epidote. In the Richmond area, however, the metabasalts contain abundant crossitic amphibole suggestive of blueschist–greenschist transition facies metamorphism (Trzcienski, 1976; Pintson, 1986). Coincidentally, this is also the area in which the volcanic sequence is thickest, and, accordingly, the rocks may have been subjected to greater load pressure. Other minerals present are Fe-Ti oxides, calcite, biotite, phengite, quartz, actinolite, titanite, and stilpnomelane. Rare kaersutitic amphibole is preserved as cores within crossite (Trzcienski, 1976; Pintson, 1986). Relict basaltic textures and sub-ophitic textures are occasionally preserved (Coish and others, 1985; Pintson, 1986). Knots of epidote occur in some of the greenschists. The proportion of such epidotised rocks (which is generally minor) varies along the metavolcanic belt.

**Metacomendites**.—The volcanic protolith of metacomendites probably consisted of lava flows as well as tuffs (Kumarapeli and others, 1989). The volcanic minerals are now represented largely by a schistose assemblage of muscovite-quartz-albite, with up to 10 percent (modal) opaques and with or without carbonate phases. However, relict phenocrysts of quartz (up to 20 percent modal) and feldspar (up to 5 percent modal) are present.Textures of feldspars suggest they were originally potassic and have been subsequently albitized.

**Metatrachytes**.—Metatrachytic rocks from the Sutton area contain relict phenocrysts of feldspar and preserve trachytic flow textures. The phenocrysts (typically less than 25
percent of the rock) are set in an inequigranular microcrystalline groundmass containing feldspar laths showing distinct, preferred orientation of their long axes. The feldspar laths in the matrix make up about 25 percent of the rock and are on average about 0.3 by 0.03 mm. The phenocrysts are generally highly sodic alkali feldspars and occur as discrete grains or clusters. The largest grain observed is 5 mm long. The microcrystalline groundmass, comprising nearly 75 percent of the rock, appears to be composed largely of feldspars (about 60 percent), minor epidote (5 percent), and opaque Fe-Ti oxides (10 percent).

Compared with the metatrachytic rocks from the Sutton area, those from the Richmond area show a higher degree of alteration. Mafic minerals have been altered to aggregates of opaque iron oxides and minor chlorite. Feldspars have undergone varying degrees of albitization but still preserve a preferred orientation of laths indicating their original trachytic flow texture. Some samples show pervasive silicification. Silica blebs in these rocks are rimmed by specks of jasper which give the rocks their pinkish and purplish colorations. Zircon is a common accessory mineral. Epidote is also present in minor amounts as a secondary phase.

ANALYTICAL TECHNIQUES

For data we used analytical techniques from previous studies on mafic and felsic rocks from: (A) Vermont area, (B) Richmond area, and (C) comendites from the Waterloo area, described in Coish and others (1985), Pintson (1986), and Kumarapeli and others (1989), respectively. The analytical techniques for the new data (presented in tables 1, 2) are described below.

Major elements.—Concentrations of the major elements (table 1) were determined on fused lithium-metaborate discs by X-ray fluorescence spectrometry (Philips PW1400 Spectrometer at McGill University) using a Rh tube operated at 40 kV and 70 mA. Loss on ignition (LOI) was determined by heating powdered samples for 50 min at 1000°C.

Trace elements.—Concentrations of Ni, Cr, Sc, V, Co, and Ba were also determined on fused discs along with the major elements as described above. Concentrations of Rb, Sr, Zr, Y, Nb, Ga, Pb, U, and Th (table 1) were determined on pressed pellets by X-ray fluorescence (operating conditions: Rh radiation, 70 kV, 40 mA). The analytical precision, as calculated from 20 replicate analyses of one sample, is better than 1 percent for most major elements and better than 5 percent for most trace elements.

Rare earths, hafnium, and tantalum.—Concentrations of fourteen rare earth elements (REE; La to Lu, all except Pm) as well as Hf and Ta (table 2) were determined by ICP-MS. The analytical procedure was as follows: (1) sintering of a 0.2 g sample aliquot with sodium peroxide, (2) dissolution of the sinter cake, separation and dissolution of the REE hydroxide-bearing precipitate, and (3) analysis by ICP-MS using the method of internal standardization to correct for matrix and drift effects. The advantage of the sintering technique is that it ensures complete digestion of resistant REE-bearing accessory phases (for example, zircon, fluorite) which may not dissolve during an acid digestion. Full details of the procedure are given in Longerich and others (1990). A pure quartz reagent blank and several certified geological reference standards as well as internal laboratory standards were analyzed with these samples. Detection limits and reagent blanks are generally about 10 percent of chondrite values. The chondrite values used for normalization are those of Taylor and McLennan (1985), compiled from Anders and Ebihara (1982) and Evensen, Hamilton, and O’Nions (1978).

For samples numbered W-01 to W-26 and RTH-3 (table 2), the concentrations of the REE (La, Ce, Nd, Sm, Eu, Tb, Yb, and Lu), along with those of Hf, Sc, and Co, were determined by instrumental neutron activation analysis (INAA) at the University of Quebec at Montreal. Precision of trace element data obtained by INAA method is
generally better than 10 percent. Details of this INAA method are given in Pintson (1986).

GEOCHEMISTRY

Major and trace element geochemistry.—The concentration of the major and minor elements of the analyzed samples are given in table 1. The Tibbit Hill volcanic assemblage spans a wide range of SiO₂ contents (44-76 wt percent), covering the entire (mafic to felsic) compositional spectrum. This wide compositional range is illustrated in figure 2. The relatively high Na content (reaching up to 10 wt percent Na₂O) of some intermediate and felsic rocks of the THF reflects the common presence of albite as observed microscopically. In the more felsic rocks, K₂O values are also highly variable (Table 1). The wide variability of the contents of the alkalies in these rocks reflects the mobility of the two elements occurring during post-magmatic alteration common in volcanic systems and during metamorphism (see below). It should be noted that alkali metasomatism is generally common in volcanic rocks due to their structure, texture, and the relatively high porosity of the intermediate and felsic volcanic rocks, as documented for several igneous complexes such as the Deloro A-type complex, Madoc, Ontario (Abdel-Rahman and Martin, 1990a).

Despite the mobility of the alkalis, the silica versus alkalis diagram of Miyashiro (1978; not shown) shows that most lithologies of the THF are alkaline. The relative enrichment of Ti within these rocks (table 1), compared to calc-alkaline volcanic rocks, is consistent with the alkaline nature of the THF. This is also reflected by the presence of kaersutitic amphibole and Fe-Ti oxides as observed petrographically.

In the Nb/Y–Zr/Ti diagram (fig. 3) of Winchester and Floyd (1977) and Floyd and Winchester (1978), rocks of the THF occupy the entire spectrum of mafic to felsic alkaline volcanic rocks (alkali basalt through comendite/pantellerite). Rocks of the THF generally exhibit a wide range of Zr (138-1493 ppm), Nb (15-139 ppm), and Y (18-185 ppm) concentrations (table 1; Coish and others, 1985; Pintson, 1986; Kumarapeli and others, 1989).

In the Tibbit Hill rocks, the Zr/Hf ratio ranges from 32 to 50 in basalts with an average of 41, which falls well within reported ratios of typical OIB-type basalts (37-43; St. Seymour and Kumarapeli, 1995). The Zr/Hf ratio of the Tibbit Hill trachytes ranges from 57 to 79, with an average of 66. The relatively wide range of the Zr/Hf ratios in the THF rocks may have resulted from minor redistribution of Hf during the metamorphic episode (see the section on the mobility of elements below).

The Nb/Ta ratio ranges from 17.7 to 18.8 in the THF basaltic rocks, with an average of 18.3, which is also comparable to Nb/Ta ratios (15-18) reported for OIB-type basaltic rocks (St. Seymour and Kumarapeli, 1995). The Nb/Ta ratio in the THF trachytes ranges from 17.7 to 19.8 (19.1 avg). In general, basaltic rocks of the THF contain relatively high concentrations of the high field strength elements (HFSE), thus reflecting an enriched source (see below). However, concentrations of U (0-5.8 ppm) and Th (0-9.4 ppm) are relatively low for such an alkaline suite.

Mobility of elements.—Results of this study are used to illustrate further the mobility of elements in response to the metamorphic episode that affected the THF rocks. Our results indicate that Ca, Na, and K exhibit wide compositional variations. The average CaO content in the THF basalt (6.05 wt percent) is well below average CaO concentration in a typical unaltered basalt (9.66 wt percent) or in a tholeiite (10.35 wt percent; Le Maitre, 1976). The average NaO content in the THF basalt (4.35 wt percent) is relatively higher than that of the average basalt (2.97 wt percent), or tholeiite (2.44 wt percent; Le Maitre, 1976). The data reflect the mobility of Ca and Na during metamorphism of the THF. The wide variability in the concentration of K in the THF basalt (ranging from
### Table 1

Chemical composition of the Tibbit Hill volcanic assemblage. Samples W-01 to DTH8 are basalts, and samples DTH1 to DTH19 are trachytes.

<table>
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<th>Sample</th>
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<th>W-13</th>
<th>W-17</th>
<th>W-21</th>
<th>W-26</th>
<th>RTH3</th>
<th>DTH5B</th>
<th>DTH6</th>
<th>DTH8</th>
<th>DTH1</th>
<th>DTH2</th>
<th>DTH3</th>
<th>DTH4</th>
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<td>46.51</td>
<td>46.81</td>
<td>46.61</td>
<td>46.13</td>
<td>46.06</td>
<td>46.31</td>
<td>50.45</td>
<td>49.84</td>
<td>54.61</td>
<td>59.97</td>
<td>53.15</td>
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<td>3.23</td>
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<td>15.23</td>
<td>15.95</td>
<td>15.84</td>
<td>16.56</td>
<td>15.33</td>
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<td>3.36</td>
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<td>1.19</td>
<td>0.40</td>
<td>0.62</td>
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</table>

| TOTAL | 102.01 | 101.45 | 102.90 | 102.56 | 102.28 | 102.11 | 100.39 | 100.54 | 100.40 | 100.69 | 100.04 | 100.49 | 100.81 | 100.34 |

V  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  |
Sr | 29.3 | 24.4 | 22.3 | 32.2 | 25.6 | 28.5 | 23.5 | 18  | 20  | 23  | 13  | 9  | 19  | 13  |
Cs | 54.2 | 46.8 | 33.4 | 48.6 | 46.3 | 52.3 | 48.1 | 78  | 30  | 22  | 23  | 16  | 23  | 29  |
C | 236  | 114  | 78.8 | 176  | 176  | 226  | 118  | 180 | 212 | 200 | 111 | 81  | 85  | 96  |
Ni | 172  | 185  | 117  | 216  | 143  | 192  | 77   | 90  | 49  | 32  | 46  | 11  | 26  | 7   |
Gά | -    | -    | -    | -    | -    | -    | 22.9 | 14.0 | 12.9 | 14.5 | 12.5 | 11.9 | 9.6  | -    |
Pb | -    | -    | -    | -    | -    | -    | 3.7  | 11.8 | 5.4  | 13.2 | 6.3  | 11.6 | 9.1  | -    |
Ba | -    | -    | -    | -    | -    | -    | 594  | 259 | 330  | 193  | 160  | 193  | 194  | -    |
Sr | 358  | 125  | 720  | 252  | 568  | 454  | 831  | 118.6 | 101.1 | 120  | 154.9 | 123  | 99.7 | 105.4 |
Nà | 29.0 | 25.0 | 33.1 | 34.7 | 20.9 | 25.8 | 14.6 | 31.5 | 26.4 | 27.6 | 31.4 | 42.8 | 29.5 | 28.3 |
Y  | 35.1 | 37.3 | 34.2 | 27.6 | 31.3 | 26.3 | 27.7 | 36.1 | 30.7 | 34.7 | 34.9 | 35.9 | 30.9 | 33.6 |
Zr  | 204  | 221  | 151  | 151  | 174  | 174  | 245.5 | 176.4 | 187.3 | 243.4 | 394.1 | 227.9 | 219.6 |
Hf  | 5.93 | 6.60 | 4.79 | 3.79 | 3.92 | 2.77 | 4.55 | 5.34 | 3.79 | -    | -    | -    | -    | -    |
Ta | -    | -    | -    | -    | -    | -    | 1.78 | 1.47 | -    | -    | -    | -    | -    | -    |
Th | -    | -    | -    | -    | -    | -    | 0.60 | 2.0  | 0.2  | 1.8  | 4.7  | 3    | 2.3  | -    |
U  | -    | -    | -    | -    | -    | -    | 0.40 | 1.6  | 0    | 1.8  | 2.4  | 0    | 2.1  | -    |
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Geochemistry and petrogenesis of the Tibbit Hill metavolcanic suite, Quebec-Vermont
Table 2

Concentrations of the rare earth elements in the Tibbit Hill volcanic assemblage. Samples W-01 to DTH8 are basalts, and samples DTH11 to DTH19 are trachytes.

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0.01-1.2 wt percent K$_2$O; table 1) suggests also that K has been highly mobile during metamorphism.

Major elements such as SiO$_2$ (ranging from 44.2 to 50.5 wt percent; Table 1), Al$_2$O$_3$ (15.23 to 16.98 wt percent), TiO$_2$ (2.22-3.14 wt percent), and P$_2$O$_5$ (0.32-0.59 wt percent) exhibit much less variations and appear to have been much less affected by the metamorphic event. The concentration of silica is still representative of the protolith and reflects its basaltic nature.

The incompatible trace elements (along with Ti and P) seem to have been least affected by metamorphism. Chondrite-normalized incompatible element patterns of the THF basaltic rocks are shown in figure 4. The wide scatter observed for K and Sr resulting from the wide ranges in their normalized abundances with strong depletion in some of the THF basaltic rocks (fig. 4) suggests that K and Sr have been highly mobile as a result of metamorphism.

Hf shows a slightly wider range than the rest of the incompatible high field strength elements. The normalized patterns of most of the other incompatible elements plotted fall within a consistently narrow range, vary systematically from one sample to another, and are relatively smooth, parallel to subparallel patterns (fig. 4). These incompatible element profiles suggest that, despite metamorphism, most of the HFSE (as Nb, Zr, Ti, and Y), along with the REE, have remained largely intact.

It should be noted that relatively smooth patterns are commonly characteristic of unaltered or fresh basalts, where normalized abundances of Zr, Ti, and Hf correlate with the REE (Sun, Nesbitt, and Sharaskin, 1979; Sun, 1980). Thus, our results suggest that most of the incompatible elements can be used in assessing the petrological character of the protolith.
Our results are also consistent with several other investigations on the mobility of elements. For example, in their investigations on the effect of alteration and metamorphism on the mobility of elements in metabasalts from other localities, Condie, Viljoen, and Kable (1977), and Muecke, Pride and Sarker (1979) have reached similar conclusions. Several other authors including Pearce and Cann (1973), Ludden and others (1982), Pintson, Kumarapeli, and Morency (1985), and Coish and others (1985) demonstrated also that Ti, Zr, Y, and the REE typically remain immobile during metamorphism.

Inter-element relationships.—Inter-element diagrams (for example, Y versus Zr and Hf; fig. 5) show a gradual increase in these incompatible elements from the less evolved to the more evolved compositions, thus suggesting a genetic link. The linear trends shown here and in figure 2 further suggest that these incompatible elements have remained immobile during metamorphism, and that their variation is, most probably, the result of a primary magmatic process such as fractional crystallization (see below).

Rare-earth element geochemistry.—The concentration of the rare-earth elements (REE) of the analyzed samples are given in table 2. The chondrite-normalized REE patterns of the three (mafic, intermediate, and felsic) volcanic lithologies show a gradual increase in the level of the REE from mafic to felsic compositions (fig. 6A; table 2). Thus, a systematic general increase of REE with differentiation (assuming that it is the operative process, see below) characterizes this suite.

The REE patterns are generally parallel to subparallel and generally uniform within each of the three rock types (basalt, trachyte, and comendite) and within the entire suite (fig. 6A), thus underlining its comagmatic nature. The light rare-earth elements (LREE)
show a pronounced fractionation compared to the heavy rare-earth elements (HREE), and all samples are LREE enriched over HREE. This is also shown by the relatively high La/Yb ratios which range from 5.2 to 11.4 in basalts, 5.5 to 8.5 in trachytes, and 6 to 16.8 in comendites (table 2; Coish and others, 1985; Pintson, 1986; Kumarapeli and others, 1989). The more felsic lithologies exhibit significant negative Eu-anomalies which gradually increase (or become larger) with increasing the concentration of REE. Early fractionation of feldspars and a higher oxidation state in the more felsic liquid are possible factors responsible for the presence of the negative Eu-anomalies in the more felsic lithologies. With the exception of minor differences, such as the concentration of Tb, the Tibbit Hill basalts from the Richmond and Sutton areas (analyzed for this study, table 2) show very similar REE patterns (fig. 6B) to THF basalts from Vermont (studied by Coish and others, 1985) and from Richmond (Pintson, 1986).

DISCUSSION

Tectonic setting.—Using standard tectonic discrimination diagrams, the Tibbit Hill basaltic rocks, with their chemical traits characteristic of “within plate basalts,” consistently reflect an anorogenic setting (fig. 7A, after Pearce and Cann, 1973; fig. 7B, after Pearce and Norry, 1979). The intermediate and felsic components of the Tibbit Hill Formation also conform to an anorogenic setting. Nb and Y, among other trace element tracers, have been used to discriminate the different tectonic settings of felsic and
Fig. 5. Variations of Y versus Zr and Hf (in ppm). Note the gradual increase of these elements from mafic to felsic compositions. Symbols as in figure 2.
Fig. 6. Chondrite-normalized plots for rocks of the THF, showing: (a) REE patterns for basalts (squares), and trachytes (circles), superimposed on an envelope (marked by diagonal lines) representing rare earth patterns of the more felsic (comenditic) rocks of Kumarapeli and others (1989), and (b) REE patterns for THF basalts reported in this study, superimposed on REE patterns for THF basalts from Coish and others (1985; shaded envelope), and those from Pintson (1986; envelope outlined by a dashed line). Note that the REE patterns of all units are uniform and conformable (see text for details). Normalization values used are taken from Taylor and McLennan (1985).
Fig. 7(A) Ti-Zr-Y triangular diagram (after Pearce and Cann, 1973). Within plate basalts (WPB; field D), ocean floor basalts (OFB; field B), low-K tholeiites (LKT; fields A, B), and calc-alkaline basalts (CAB; fields B,C). (B) Zr versus Zr/Y diagram (after Pearce and Norry, 1979), showing the within-plate tectonic environment of the Tibbit Hill basaltic rocks. Symbols as in figure 2.
intermediate magmas (Pearce, Harris, and Tindle, 1984). Most samples plot in the field of within-plate complexes (fig. 8), as is typical of A-type suites from other regions worldwide (Collins and others, 1982; Whalen, Currie, and Chappell, 1987; Abdel-Rahman and Martin, 1990b; Eby, 1992). The anorogenic geochemical affinities of all rock types of the Tibbit Hill volcanic assemblage are consistent with its inferred geological setting at the rifted continental margin of Laurentia.

Dike Swarms and the THF Basalt. —U-Pb baddeleyite and zircon ages of the Grenville dike swarm indicate a single age of emplacement at 590 ±2/−1 Ma (Kamo, Krogh, and Kumarapeli, 1995). Determining the precise U-Pb age of the Adirondack dike swarm will help establish whether the two swarms (Adirondack and Grenville) represent a single, large, coeval radial swarm. To our knowledge, this has not yet been done, and the only available isotopic age data for the Adirondack dike swarm consists of an unpublished K-Ar and 40Ar/39Ar age of 588 Ma (Coish and Sinton, 1992).

As summarized above, the THF basalt was emplaced (555 Ma; Kumarapeli and others, 1989) about 35 Ma after the emplacement of both the Grenville dike swarm (590 Ma; Kamo, Krogh and Kumarapeli, 1995) and the Adirondack dike swarm (588 Ma; Coish and Sinton, 1992). Geochemically, the THF basalt is an evolved, within-plate, mildly alkaline suite which is enriched in the incompatible elements including the REE with strong LREE enrichment over the HREE.

Gabbroic rocks of the Grenville dike swarm in Ontario and Quebec (compare fig. 1) are similar mostly to saturated quartz tholeiites, with a few samples representing transitional basalts. The overall chemistry of the gabbroic Grenville dikes is typical of continental flood basalts. The estimated principal source of the tholeiitic basaltic melt
that produced the Grenville dike swarm some 35 Ma prior to the emplacement of the THF basalt was derived from a mixed source consisting of a major depleted N-MORB source and a minor fertile P-MORB source with a ratio of 6:1, respectively (St. Seymour and Kumarapeli, 1995).

Based on the available isotopic age data, the Adirondack dike swarm (588 Ma) in northeastern New York State seems to be correlative to the Grenville dike swarm (590 Ma). Geochemically, however, the two dike swarms differ significantly. Unlike the Grenville, the Adirondack dikes are of a very enriched nature. The Adirondack dike rocks consist mostly of olivine and nepheline-normative basalts of alkaline affinity and represent within-plate lavas. These rocks exhibit relatively high concentrations of Ti, P, K, Zr, Y, and REE, with strong LREE enrichment over HREE (Coish and Sinton, 1992; Badger, 1993, 1994; Badger, Olmsted, and Whitney, 1996). These geochemical characteristics suggest a trace element-enriched asthenospheric source (OIB-like source) for the Adirondack dike swarm, and an estimated depth of melt segregation of 70 to 100 km (Coish and Sinton, 1992; Badger, 1994). With its very enriched nature, the Adirondack basaltic dike swarm is thus similar geochemically to the THF basalt, and both differ from the rather geochemically depleted Grenville dike swarm.

**Petrogenetic indicators.**—Bonin (1990) recognized the distinctive nature of A-type magmas and subdivided them into two groups: post-orogenic and early anorogenic. Eby (1990, 1992) subdivided the A-type felsic and intermediate magmas into two groups: A1 which represents differentiates of mantle-derived basaltic magmas (anorogenic or rift zone magmas), and A2 which represents crustal-derived magmas of a post-orogenic setting. The Y/Nb-Yb/Ta systematics of the Tibbit Hill felsic and intermediate rocks (fig. 9; Eby, 1990; 1992) suggest they were probably the product of fractionation of a more mafic precursor (similar to that of ocean island basalts, OIB) which was originally derived from a mantle source. It should be noted that the trace element characteristics of OIBs are generally similar to those of continental anorogenic basalts, and together they constitute within-plate basalts (Pearce and Cann, 1973).

Since the Tibbit Hill basalts are within-plate anorogenic basalts (fig. 7), they constitute the most obvious source from which the intermediate and felsic rocks fractionated.

Furthermore, diagrams designed to discriminate between the A1 and A2 groups of anorogenic magmas indicate that the Tibbit Hill intermediate and felsic rocks belong mostly to the A1 group (fig. 10), representing differentiates of within-plate basalts, typically related to hotspots, plumes, or continental rift-zones (Eby, 1992). Thus, a mantle derived, rift-related, basaltic magma most likely represents the parent liquid which fractionated to produce the intermediate and felsic rocks (see below).

**A plume source for the Tibbit Hill basalts.**—It has been argued that the Tibbit Hill volcanism occurred at the Sutton Mountains triple junction which was probably one of several key lithospheric ruptures that linked to initiate continental breakup as a prelude to the opening of the Iapetus ocean (Kumarapeli, 1985, 1993). While the sweeping arc of the Sutton Mountains salient is probably inherited from the geometry of the triple junction (Dewey and Burke, 1974), the triangular-shaped area representing the subsurface extension of the Tibbit Hill volcanic mass from gravity interpretation (fig. 1) is the expected shape of a volcanic shield at an RRR triple junction.

Other evidence supporting the triple junction hypothesis include a well-defined rift zone (Ottawa graben) which is interpreted as the failed arm and a approx 590 Ma giant swarm of mafic dikes (the Grenville dike swarm) which appears to radiate from the triple junction (Kumarapeli, 1993; Kamo, Krog, and Kumarapeli, 1995; fig. 1). The available age of the Adirondack dike swarm (588 Ma) suggests that this dike swarm may also be related to this triple junction (Kumarapeli and Isachsen, 1991). The stratigraphy and sedimentology of the Lower Oak Group are also consistent with the triple junction
concept (Cady, 1969; Marquis and Kumarapeli, 1993). The time gap between dike emplacement (588-590 Ma) during initial rifting and volcanism (555-560 Ma) is consistent with the plume model of White and McKenzie (1989), which predicts significant crustal extension and rifting prior to volcanism.

It has also been argued that the Sutton Mountains triple junction formed over a rising mantle plume (Kumarapeli, 1993; see also Burke and Dewey, 1973). The earliest magmatism related to this plume was the emplacement of the strongly oriented, about 590 Ma Grenville dike swarm (Kamo, Krogh, and Kumarapeli, 1995; also see Campbell and Griffiths, 1991) whose overall geochemical affinities are typical of continental flood basalts (St. Seymour and Kumarapeli, 1995). Continued plume activity is indicated by the emplacement of several alkalic and carbonatitic complexes in eastern Canada around 575 Ma (Doig, 1970; Lumbers, 1971; Symons and Chiasson, 1991).

The Tibbit Hill volcanism appears to have been a relatively short-lived event that took place at the triple junction during some 30 to 35 Ma after the first pulse of plume-related magmatism that gave rise to the dike swarms. The THF volcanism is thus the youngest, pre-breakup, extension-related volcanism known from the continental margin of Laurentia and may have formed during a rapid phase of rifting and crustal stretching prior to the initiation of seafloor spreading (White and McKenzie, 1989; Kumarapeli, 1993). Based on the plume models of White and McKenzie (1989) and Campbell and Griffiths (1990), Kumarapeli (1993) proposed that the mildly alkaline basaltic magma of the THF formed from the hotter mantle at the plume axis beneath the

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**Fig. 9.** Y/Nb versus Yb/Ta diagram (after Eby, 1990, 1992): OIB = field for oceanic island basalts and IAB = field for relatively Nb and Ta enriched island arc basalts. This plot suggests a OIB-type source for the more evolved rocks of the Tibbit Hill suite. Symbols as in figure 2.
attenuated continental lithosphere, whereas the tholeiitic basaltic liquid of the Grenville dike swarm formed from cooler parts of the hybrid mantle in the plume head.

Our analysis of the geochemical data shows that the Tibbit Hill felsic and intermediate volcanic rocks belong mostly to the A1 group (fig. 10), representing differentiates of within-plate basalts, typically related to hotspots, plumes, or continental rift-zones (Eby, 1992). The data also show that the THF basalts geochemically resemble a fertile or plume-related MORB (P-MORB) compared to basalts derived from a depleted, transitional, or normal-MORB (T-MORB or N-MORB; Menzies and Kyle, 1990), as they exhibit relatively higher concentrations of Zr and Nb but lower concentrations of Y than basalts characteristic of T-MORB or N-MORB (fig. 11). Similar conclusions were reached by Coish and others (1985) and Pintson (1986) from the studies of their respective areas. Thus, a plume-source origin is well supported by the geochemistry of the Tibbit Hill volcanic suite.

Partial melting and the origin of the Tibbit Hill basalts.—The general enrichment of HFS elements in the THF basaltic rocks, along with their relatively high La/Yb ratios, suggests that these rocks were derived from a fertile mantle source. To test this hypothesis, partial
melting modelling for REE was performed, using the batch melting equations of Shaw (1970). The calculations were done using two model source compositions. The compositions used are those of a primitive mantle using REE concentrations from Sun and McDonough (1989) and a mixed (50 percent primitive—50 percent depleted) mantle source using REE concentrations from McKenzie and O’Nions (1991). Residual mineralogy varied between those of spinel- and garnet lherzolite. Spinel, garnet, and clinopyroxene were assumed to decrease in abundance linearly with increasing degrees of partial melting, as they are typically consumed at less than 25 percent partial melting (McKenzie and O’Nions, 1991; Lassiter, DePaolo, and Mahoney, 1995).

Model proportions and melting proportions used are given in table 3 and are generally similar to those used in other partial melting calculations (Hanson, 1980; McKenzie and O’Nions, 1991; Witt-Eickschen and Kramm, 1997). Thus, modelling was performed using three different mantle mineral assemblages: spinel lherzolite, garnet lherzolite, and spinel-garnet lherzolite, for both a primitive- and a mixed source composition. The partition coefficients used are from McKenzie and O’Nions (1991).

The results of the mantle melt modelling (presented in table 3 and fig. 12) show that:

A. No spinel is required in the mantle source, but garnet is a required phase. The relatively low Sc contents in the THF basalts (table 1, 18-32 ppm; Coish and others, 1985; Pintson, 1986) also indicate that clinopyroxene and/or garnet were important phases during the melting event.
B. Neither depleted nor mixed primitive/depleted mantle material represent the mantle source for the THF basalt. The THF basalt was generated by partial melting of a primitive mantle source.

C. Only a small degree of partial melting of a primitive source was required to generate the THF basaltic magma. The REE pattern of the calculated liquid produced by 2.5 percent batch partial melting of a garnet lherzolite (of a primitive mantle composition) closely matches that of the least differentiated (or most primitive) THF basaltic composition (sample #RTH-3; table 3, fig. 12). The latter sample, containing the lowest measured REE concentrations and with a Zr/Hf ratio of 38 which is typical of the mantle, is assumed to represent a merely primitive THF basaltic magma. Melting probably took place within the thermal anomaly associated with the rising mantle plume beneath the Sutton Mountains RRR triple junction, as inferred from geochemical and tectonic data.

Minor differences occur between the concentrations of Nd and Yb (14 and 16 percent, respectively) of the calculated model liquid and those for the observed melt (basalt sample #RTH-3; table 3). It should be noted that Frey, Green, and Roy (1978) considered that up to a 15 percent difference between calculated and observed melts represented excellent agreement. A larger discrepancy, however, occurs for the concen-

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**Table 3**

*Model parameters and results of batch partial melting calculations using various mineralogical and chemical compositions of primitive- and mixed mantle sources*

<table>
<thead>
<tr>
<th>Phase</th>
<th>Starting mode</th>
<th>Melt mode</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>a</td>
<td>b</td>
</tr>
<tr>
<td>Olivine</td>
<td>0.57</td>
<td>0.55</td>
</tr>
<tr>
<td>Opx</td>
<td>0.25</td>
<td>0.25</td>
</tr>
<tr>
<td>Cpx</td>
<td>0.15</td>
<td>0.15</td>
</tr>
<tr>
<td>Garnet</td>
<td>0.00</td>
<td>0.02</td>
</tr>
<tr>
<td>Spinel</td>
<td>0.03</td>
<td>0.03</td>
</tr>
</tbody>
</table>

Calculated melts produced by 2.5 percent batch partial melting are #1 to #6, and the measured, least differentiated, THF basalt is #7. The starting mode, melt mode, and mantle source type used to produce each of the calculated melts are as follows:

Melt #1: starting mode a, melt mode a, mixed source,
Melt #2: starting mode b, melt mode b, mixed source,
Melt #3: starting mode c, melt mode c, mixed source,
Melt #4: starting mode a, melt mode a, primitive source,
Melt #5: starting mode b, melt mode b, primitive source,
Melt #6: starting mode c, melt mode c, primitive source.

Note that the composition of the calculated melt #6 (produced by 2.5 percent melting of a garnet lherzolite of a primitive mantle source) closely match that of the measured, least differentiated THF basalt (#7). See text for details.
tration of Tb between calculated and observed melts (1.2 and 0.81 ppm, respectively; table 3). Such a large difference between calculated and observed liquids is primarily due to uncertainties in phase proportions and distribution coefficients (KD's). As an example, KD values reported in the literature for Tb (between garnet and basaltic melts) vary greatly from 0.26 (Frey, Green, and Roy, 1978) to 7.1 (Henderson, 1982).

Our results of mantle modelling for the THF basaltic rocks of the Richmond and Sutton areas are consistent with those for THF basalts from Vermont as given in Coish and others (1985). Coish and others (1985) concluded that the THF basaltic magma from Vermont was produced by 2.5 percent melting of a mantle source with a composition of chondrite and a mineralogy consisting of 65 percent Ol, 20 percent opx, 13 percent cpx, and 2 percent garnet, using partition coefficients of Frey, Green, and Roy (1978).

As demonstrated by McKenzie and O’Nions (1991) and Lassiter, DePaolo, and Mahoney (1995) results of REE modelling place some constraints on the approximate depth of melting and magma formation. The transition from garnet to spinel peridotite takes place between a depth of about 60 to 80 km for normal mantle and about 80 to 100 km within hot mantle plumes (McKenzie and O’Nions, 1991).

Possible depth of melting.—Based on the study of McKenzie and O’Nions (1991), Ellam (1992) investigated the relationship between trace element compositions of basalts, variations in thickness of the lithosphere, and final depths of melt segregation. Thus, Ellam (1992) formulated a method to estimate depths of extraction of final melts.
produced at depths shallower than 125 km near the lithosphere-asthenosphere interface. Using this method, curves corresponding to the Ce, Sm, and Yb concentrations of the Tibbit Hill basalts all produce a final melt segregation depth of about 100 km. As pointed out by Ellam (1992), the usefulness of using abundances of Ce, and Sm to estimate such depths is limited by the differential effects of fractional crystallization in variably evolved basalts, whereas REE ratios such as Ce/Yb offer sensitive indicators of changing lithospheric thickness because they will not be radically affected by fractional crystallization. In the Tibbit Hill case, the Ce/Yb ratio (with an average of 20.8) indicates a final basaltic melt segregation depth of about 80 km (that is, within the garnet lherzolite zone). This interpretation is consistent with the composition of the REE in the THF basalts (LREE enriched over HREE) and further suggests that the source was garnet-bearing. The estimated depth of 80 to 100 km for the segregation of the plume-related THF basaltic magma is consistent also with the depth of melt segregation (70-100 km) estimated for the geochemically similar mildly alkaline basalts of the Adirondack dike swarm (Badger, 1994).

Fractionation of the basaltic magma.—Field relations, combined with volume considerations, along with the chemical characteristics described above (compare figs. 9 and 10), indicate that the minor felsic and intermediate components of the THF are not crust-derived. On the contrary, these rocks represent differentiates of a mantle-derived basaltic magma as they belong to the A1 group of anorogenic suites. No field or other evidence was found to suggest that processes such as assimilation or magma mixing were responsible for the evolution of this volcanic assemblage.

The linear geochemical trends (compare A and B of fig. 5) and the parallel nature of the normalized REE patterns with increasing total abundance of the REE from mafic to intermediate to felsic lithologies (fig. 6A) suggest that the trachytes and comendites represent differentiates of the THF basaltic magma. In the La/Sm versus La diagram (fig. 13) data points from this study plot along a nearly horizontal line, a feature restricted to the process of fractional crystallization (Allegre and Minster, 1978).

Several studies have favored fractionation from basaltic parental magmas as the process responsible for the formation of associated felsic lavas, such as those in the East

![Fig. 13. La/Sm versus La diagram showing that the data points from this study plot along a nearly horizontal trend. The dashed line represents a linear regression line through the data points of this study. Data points of Coish and others (1985) and Pintson (1986) are also plotted for reference. Symbols as in figure 2.](image-url)
African rift systems in Kenya (Nash, Carmichael, and Johnson, 1969; Weaver, Sceal, and Gibson, 1972) and in the Boina centre of the Afar rift in Ethiopia (Barberi and others, 1975; Bizouard, Barberi, and Varet, 1980).

It should be noted, however, that the presence of large volume of felsic rocks in association with basaltic rocks and the lack of intermediate compositions in bimodal volcanic centers have been used by many authors as arguments against the derivation of felsic magmas from their associated mafic magmas. In the THF case, however, intermediate compositions do exist but in minor volumes, and the felsic comenditic rocks, also, do not occur in large volumes. This observation, along with other features (as discussed above), are consistent with our interpretation that fractionation played a significant role during the evolution of this volcanic assemblage.

A modern analogue for the Tibbit Hill volcanic assemblage.—Several lines of evidence show the striking similarities between the Tibbit Hill volcanic rocks and those of the Afar rift. These include:

A. Volcanic assemblages from both regions are mildly alkaline and include basaltic, trachytic, and comenditic/pantelleritic compositions (for example, the Boina centre of the Afar rift in Ethiopia; Barberi and others, 1975; Bizouard, Barberi, and Varet, 1980).

B. The THF volcanic assemblage and that from the Afar rift are enriched in incompatible elements including the REE and exhibit similar incompatible trace element patterns (Barberi and others, 1975; Bizouard, Barberi, and Varet, 1980; Kumarapeli and others, 1989). The chondrite normalized incompatible element patterns (using normalization values of Taylor and McLennan, 1985), for representative samples from the two suites (fig. 14) indicate that the two suites generally exhibit similar, parallel to subparallel patterns, but with incompatible element enrichment (except Sr) in the Tibbit Hill basaltic rocks, because the THF basalts are more evolved.

C. Standard tectonic discrimination diagrams (compare figs. 7 and 8) show that the THF mafic to felsic volcanics are clearly the product of within-plate, anorogenic, rift-related volcanism most likely associated with RRR triple junction. These resemble the tectonic environment of the east African rift volcanics (White and McKenzie, 1989), as well as those of the Boina Center of the Afar rift, Ethiopia (Barberi and others, 1975).

D. Primary magmas of the volcanic rocks in both regions have been interpreted to be plume-generated (White and McKenzie, 1989; and this study).

E. The formation of the more felsic volcanic lithologies in both cases has been interpreted to be the result of fractionation of their associated basaltic magmas (Weaver, Sceal, and Gibson, 1972; and this study).

Thus, the Afar rift volcanic assemblage in Ethiopia appears to represent a modern analogue to the Tibbit Hill volcanic lithologies.

CONCLUSIONS

1. The Tibbit Hill Formation covers a large crustal segment exposed along a belt about 250 km long in the Appalachian fold belt (Quebec-Vermont). It is predominantly basaltic in composition and contains a minor component of felsic and intermediate alkaline volcanic lithologies. Therefore, it is not strictly bimodal (basaltic-comenditic) but contains a spectrum of compositions ranging from alkali basalt to trachyte and comendite.

2. Geochemically, the rocks are mildly alkaline to subalkaline in nature and are relatively enriched in incompatible elements. The concentrations of the HFSE and the REE gradually increase from alkali basalt to trachyte to comendite, and the chondrite normalized patterns are fractionated, parallel to subparallel, generally uniform, and conformable, but with negative Eu-anomalies developed in the more felsic varieties. These geochemical features underline the comagmatic nature of the entire volcanic assemblage and are consistent with a fractionated basalt to comendite suite.
3. The incompatible element profiles suggest that most of these elements including Nb, Zr, Ti, Y, and the REE have not been affected by metamorphism, as they remained largely intact within the THF rocks.

4. On several standard tectonic discriminant diagrams, all rock types display the geochemical characteristics of within-plate lavas. This is consistent with the regional geological context in which the volcanism, associated with an Iapetan RRR triple junction, occurs shortly before the onset of sea floor spreading.

5. Chemical characteristics of the intermediate and felsic rocks suggest they are not crust-derived but belong to the A$_2$ group of anorogenic magmas, representing differentiates of within-plate basalts which are related to hotspots, plumes, or continental rift zones. Chemical characteristics of the basaltic rocks suggest that their melts were derived from a fertile or plume-related mantle source. The overall data are consistent with a plume-origin for the Tibbit Hill basalts.

6. Geochemical modelling shows that the THF basaltic magma was produced by a very small degree of batch partial melting (F = 2.5 percent) of a garnet-bearing primitive mantle source (garnet lherzolite). A final basaltic melt segregation depth is estimated at 80 to 100 km. Melting probably occurred within the thermal anomaly of a rising mantle plume beneath the Sutton Mountains RRR triple junction, as inferred from geochemical and tectonic data. Minor trachytic and comenditic lithologies were produced by fractionation of the basaltic magma. A modern analogue to the THF volcanic rocks is represented by the volcanic assemblage of the Afar rift.
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