Silurian-Early Devonian mafic rocks of the Piscataquis volcanic belt in northern Maine

R. Hon, J.P. Fitzgerald, S.L. Sargent, W.D. Schwartz
Department of Geology and Geophysics, Boston College, Chestnut Hill, Massachusetts 02167, U.S.A.
J. Dostal
Department of Geology, Saint Mary's University, Halifax, Nova Scotia B3H 3C3, Canada
and
J.D. Keppie
Nova Scotia Department of Mines and Energy, P.O. Box 1087, Halifax, Nova Scotia B3J 2X1, Canada

Date Received July 8, 1991
Date Accepted November 13, 1991

The Silurian-Early Devonian eruptive rocks at selected sites in the Piscataquis volcanic belt in northern Maine are composed of mafic and felsic rocks with rare intermediate types. The mafic rocks are mainly basalts that are commonly strongly fractionated and have the characteristics of intraplate continental tholeiites. The mantle-normalized incompatible trace element patterns of the rocks display negative Nb-Ta anomalies that were probably inherited from sub-continental lithosphere modified by pre-Silurian subduction processes. However, they do not have Ti depletion typical of subduction-related magmas. On the other hand, the youngest (late Early Devonian) Edmunds Hill Formation is composed of calc-alkali andesites that exhibit features typical of arc-related magmas. The Silurian-Early Devonian volcanic rocks were primarily erupted in a within-plate extensional environment that terminated with limited subduction. This extensional environment is inferred to be associated with the sinistral accretion of the Avalon Composite Terrane that produced an oblique pull-apart rift in adjacent Laurentia.

Introduction

The Piscataquis volcanic belt is broadly defined as a zone of discontinuous suites of Silurian-Early Devonian volcanic rocks that lie within the Connecticut Valley-Gaspé Synclinorium in Maine and adjacent Quebec (Fig. 1). Originally this definition was restricted to rhyolitic members of the Moose River and Traveler Mountain region (locality 1 on Fig. 1) (Rankin, 1968). However, it has been expanded to include all the other volcanic suites of similar age within the same tectonic domain (Osberg et al., 1989). To the northeast, the Piscataquis volcanic belt merges with the Tobique volcanic belt that extends from the Gaspé Peninsula along the northwestern margin of the Miramichi Highlands in New Brunswick (Bedard, 1986; Dostal et al., 1989). To the southwest, the Piscataquis volcanic belt apparently dies out although some isolated occurrences of Early Devonian volcanic rocks occur in western New Hampshire and central Vermont.

The volcanic rocks are mainly of Late Silurian and Early Devonian age with a few ranging down to Early Silurian. They are interbedded with and grade laterally into sedimentary rocks that form part of a Silurian-Devonian overstep sequence deposited unconformably across the North American craton and several accreted Cambrian-Ordovician terranes (Keppie, 1989). Coeval intrusive bodies with ages ranging between 415 and 375 Ma occur in the Greenville plutonic belt (lying just south of the Piscataquis volcanic belt), be-
Fig. 1. Map of the northern part of the mainland Appalachians showing the distribution of Silurian-Devonian volcanic and sedimentary rocks, associated negative Bouguer anomalies and a region of most intense Devonian deformation. Numbers 1 to 4 show the locations of analyzed mafic volcanic rocks and the stratigraphic columns shown in Figure 2.

tween the Piscataquis and Tobique volcanic belts (Osberg et al., 1985) and in the Miramichi Highlands (Bevier and Whalen, 1989).

The Silurian-Early Devonian Piscataquis rocks have commonly been interpreted as a volcanic arc built upon the edge of cratonic North America related to the Acadian convergence and subduction (e.g., Rankin, 1968; Bradley, 1983; Thirwall, 1988). However, recent studies on equivalent volcanic rocks of the Tobique volcanic belt in New Brunswick and Gaspé have shown that the basalts were erupted in a continental rifting environment in an orogenic foreland (Laurent and Belanger, 1984; Bedard, 1986; Dostal et al., 1989). This brings into question the nature of the Piscataquis volcanic belt. This paper presents geochemical data for the Silurian-Devonian rocks of the Piscataquis volcanic belt in Maine which indicate that most of them were also erupted in a continental rift environment.

Geological Setting

The Piscataquis volcanic belt is generally envisaged to have formed a string of volcanic centres that provided local detritus to the neighbouring sedimentary basins: the Connecticut Valley-Gaspé trough to the north and the Matapedia-Aroostook-Merrimack trough to the south (Osberg et al., 1989). The Silurian rocks of the Connecticut Valley-Gaspé trough in Maine and adjacent Quebec consist of a southeastward thickening sequence (ca. 1000 to 5500 m) of shallow marine shelf sedimentary rocks. They have been subdivided into Lower Silurian basal lithic wacke and conglomerate, shale, tuff and minor volcanic rocks overlain by Upper Silurian sandstone, limestone, shale, volcanic rocks, siltstone and conglomerate (Boucot, 1968; Lajoie et al., 1968). The rocks of the Matapedia-Aroostook-Merrimack trough in Maine consist of beach and reef deposits (sandstone, conglomerate and limestone) fringing local volcanic centres in the Piscataquis volcanic belt that grade quickly southward into ca. 5000 to 6000 m thick turbidite fans (wacke and shale) interrupted in places by graphitic shale, limestone and well-sorted sandstone (Pavlides, 1974; Roy and Mencher, 1976).

The Silurian rocks of the Connecticut Valley-Gaspé and Matapedia-Aroostook-Merrimack troughs are overlain by Lower Devonian flysch derived from northeastern, eastern and southeastern sources in such abundance that it supplied detritus to both troughs (Boucot et al., 1964; Hall et al., 1976). Rock types grade from sandstone along the basin margins through interbedded shale and limestone to wacke and shale in the basin centres. The presence of the Lower Devonian sandstone wedges suggest coalescing deltas (ca. 260 m thick) which grade westwards into prodelta marine slope deposits up to 4000 m thick (Hall et al., 1976).

Volcanic rocks are exposed over a distance of about 160 km along the axis of the Piscataquis volcanic belt (Fig. 1) and reach a thickness of 3000 m. The three main sections of Silurian-Devonian rocks examined in this study are located in the Katahdin, Spider Lake and Presque Isle areas with a subsidiary section in the Fivemile Brook region (Figs. 1, 2).

In the Katahdin area (Figs. 1, 2), the basal Lower Silurian conglomerate is overlain by interbedded sandstone and limestone containing the latest Llandoveryan or Wenlockian fossils. These are succeeded by the Ripogenus Formation which consists of twelve mafic flows interbedded with calcareous
Lake Formation is overlain by flysch of the Seboomook Ludlovian and lowermost Devonian (Hall, 1970). The Spider Fossils in the Spider Lake Formation indicate that it spans the range in thickness from 0.5 to 10 m, are commonly massive about 800 km² (Osberg class, clinopyroxene and Fe-Ti oxides. Pillow lavas are rare. 

sandstone and massive limestone outcropping over an area of deformation and metamorphism. 

The Spider Lake Formation (Figs. 1, 2) consists of about 3200 m of subaqueous-subaerial basalts and pyroclastic rocks interbedded with basal conglomerate, fossiliferous shale, sandstone and massive limestone outcropping over an area of about 800 km² (Osberg et al., 1983). The basal lava flows range in thickness from 0.5 to 10 m, are commonly massive with vesicular flow tops, and contain phenocrysts of pyroxene and plagioclase set in a groundmass composed of plagioclase, clinopyroxene and Fe-Ti oxides. Pillow lavas are rare. Fossils in the Spider Lake Formation indicate that it spans the Ludlovian and lowermost Devonian (Hall, 1970). The Spider Lake Formation is overlain by flysch of the Seboomook Formation. The whole sequence was gently folded and metamorphosed to sub-greenschist facies. 

The northernmost outlier of volcanic rocks examined in this paper occur in the Fivemile Brook area of northern Maine (Figs. 1, 2). The Fivemile Brook Formation concordantly overlies the Caradocian-middle Llandovery Depot Mountain Formation apparently with a minor hiatus (Roy, 1989). The shallow marine Fivemile Brook Formation consists of interlayered phylite, limestone, basalt (2-31 m thick flows) and contains Ludlovian fossils. This formation is generally in fault contact with the overlying Early Devonian flysch of the Seboomook Formation. Locally, the Rocky Mountain quartz latite laterally replaces the Fivemile Brook Formation (Roy, 1989). It consists of ca. 1000 m of predominantly felsic lithic and crystal tuff with minor intercalated basalt. The Fivemile Brook mafic rocks range from the aphanitic types with vesicles or amygdules to porphyritic varieties containing plagioclase and clinopyroxene phenocrysts. The groundmass of the aphanitic rocks and associated minor intrusions have subophitic to interstertal textures composed of plagioclase, clinopyroxene and Fe-Ti oxides. The amygdules are generally filled with calcite rimmed by chlorite and epidote. The rocks have suffered open folding and sub-greenschist facies metamorphism. 

The Dockendorff Group is exposed in an outlier at the eastern end of the Piscataquis volcanic belt in the Presque Isle area (Figs. 1, 2). In this area, Upper Ordovician-Lower Silurian calcareous slate, wacke and limestone of the Carys Mills Formation are conformably overlain by clastic to calcareous mudstone, and these are, in turn, overlain by turbidites of the late Middle Silurian Jemtland Formation (Roy and Mencher, 1976). All of these units are overlain by the Lower Devonian units: Hedgehog Formation (ca. 1600 m thick succession of mafic volcanic rocks succeeded by predominant rhyolites and tuffs) and the Edmunds Hill Formation (ca. 1200 m of andesite). The mafic flows of the Hedgehog Formation are fine-grained and commonly contain feldspar phenocrysts. The Hedgehog rhyolites are typically eutaxitic ignimbrites with crystal and vitric tuffs that contain both quartz and feldspar phenocrysts, and welded pumice fragments set in a vitroclastic matrix consisting mainly of quartz, feldspars and accessory Fe-Ti oxides, biotite and apatite. These rocks are associated with tuffs that may contain vesicles, lithic fragments and feldspar crystals. The secondary minerals of the felsic rocks include sericite, epidote, chlorite and calcite. The overlying Edmunds Hill andesite is divisible into a lower pyroxene-bearing member and an upper biotite-bearing member (Boucot et al., 1964). The lower member contains phenocrysts of feldspar and pyroxene in a pilo-tactitic matrix, whereas the upper member is darker in colour and has hyaloplitic texture. The Dockendorff Group was deformed by open folds accompanied by prehnite-pumpellylite metamorphism (Richter and Roy, 1976) before being unconformably overlain by clastic sedimentary rocks of the late Middle Devonian Mapleton Formation (White and Roy, 1975).
Geochemistry

Sampling and Analytical Methods

Mafic volcanic rocks form a small proportion of the volcanic rocks of the Piscataquis belt. However, because of their crucial role in determining the tectonic setting, they were preferentially selected for analyses for this paper. Systematic sampling of the volcanic rocks at each locality was followed by the petrographic investigation to select the lavas for chemical analyses. A total of 96 lava samples were analyzed. Detailed sample locations, individual petrographic descriptions and complete analytical data are available in Fitzgerald (1991), Sargent (1985) and Schwartz (1991). Representative analyses are presented in Table 1.

The major element compositions of the samples from the Dockendorff area were determined by atomic absorption at Boston College. Major elements in the other samples were analyzed by X-ray fluorescence. The trace elements Rb, Ba, Sr, Y, Zr, Nb, Th, Ta, Hf and Co were determined by X-ray fluorescence while the instrumental neutron activation technique was employed for the determination of the rare-earth elements (REE), Sc, Th, Ta, Hf and Co. The analytical error for the trace element analyses is generally smaller than 5%. The X-ray fluorescence analyses were done at Saint Mary's University while neutron activation was done at Boston College.

Alteration

Although every effort was made to acquire the freshest possible samples, all of the volcanic rocks are affected to some degree by alteration processes. The alteration effects are manifested particularly by elevated contents of LOI and the scatter of alkalies. Most other elements do not appear to be significantly affected by alteration because they retain concentrations that are similar to those of recent volcanic suites. Furthermore, the least altered rocks generally have chemical compositions similar to rocks which are extensively replaced by secondary minerals. This similarity indicates that the present contents of most elements of the rocks approximate the primary magmatic concentrations.

Whole-Rock Geochemistry

The Silurian-Devonian extrusive rocks in the Piscataquis volcanic belt show considerable diversity (Fig. 3; Table 1). In the Katahdin area, basalts of the Ripogenus Formation are overlain by Traveler and Kineo dacites and rhyolites. On the other hand, the Spider Lake and Fivemile Brook formations are composed predominantly of basalts with rare andesites. In the Presque Isle area, the Devonian Hedgehog Formation composed of a bimodal basalt-rhyolite sequence is overlain by andesitic lavas of the Edmunds Hill Formation.

The mafic and intermediate rocks can be divided into two distinct types: (1) intraplate basalts with subordinate basaltic andesites and andesites (Katahdin, Spider Lake, Fivemile Brook and Hedgehog Formations); (2) exclusively subduction-related andesites with ~60% SiO₂ (Edmunds Hill Formation).

The intraplate mafic rocks are mainly basalts with about 48 to 53% SiO₂ (on LOI-free basis) and have variable Mg #s (mole Mg/Mg+Fe) indicating extensive fractional crystallization. The basalts display typical tholeiitic fractionation.

### Table 1. Chemical composition of representative Silurian-Early Devonian mafic rocks of the Piscataquis belt.

<table>
<thead>
<tr>
<th>KATAHDIN</th>
<th>SPIDER LAKE</th>
<th>FIVE MILE</th>
<th>HEDGEHOG</th>
<th>EDMUNDS HILL</th>
</tr>
</thead>
<tbody>
<tr>
<td>RP-2</td>
<td>RP-3</td>
<td>RP-4</td>
<td>RP-5</td>
<td>RP-6</td>
</tr>
<tr>
<td>SiO₂ (wt%)</td>
<td>54.75</td>
<td>51.27</td>
<td>51.28</td>
<td>56.76</td>
</tr>
<tr>
<td>TiO₂</td>
<td>3.29</td>
<td>3.19</td>
<td>3.12</td>
<td>3.32</td>
</tr>
<tr>
<td>MnO</td>
<td>0.23</td>
<td>0.23</td>
<td>0.20</td>
<td>0.30</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>4.32</td>
<td>4.07</td>
<td>4.77</td>
<td>4.38</td>
</tr>
<tr>
<td>MgO</td>
<td>2.08</td>
<td>1.76</td>
<td>1.91</td>
<td>2.27</td>
</tr>
<tr>
<td>H₂O</td>
<td>0.07</td>
<td>0.10</td>
<td>0.08</td>
<td>0.07</td>
</tr>
<tr>
<td>LOI</td>
<td>0.45</td>
<td>0.47</td>
<td>0.48</td>
<td>0.55</td>
</tr>
<tr>
<td>Mg#</td>
<td>0.47</td>
<td>0.45</td>
<td>0.54</td>
<td>0.48</td>
</tr>
</tbody>
</table>

---

### Notes

- **LOI**: loss on ignition; **nd**: not determined; major elements recalculated to 100% (on LOI-free basis).
trends of increasing Fe, Ti and V with differentiation which is accompanied by relatively high and constant Ti/V ratios (Fig. 4) characteristic of within plate tholeiitic basalts (Sher­vais, 1982). The REE patterns (Fig. 5) are moderately en­riched in light REE (LREE) with La/Yb ratios mostly be­tween ~3 and 5 although some samples have La/Yb > 10. The strongly differentiated basalts and basaltic andesites have higher abundances of REE but their patterns are approxi­mately parallel to those of basalts and show an Eu de­pletion. The mantle-normalized incompatible trace element plots (Fig. 6) show an enrichment of large-ion-lithophile-elements (LILE) relative to heavy REE and high-field-strength ele­ments (HFSE) and exhibit distinct negative Nb and Ta anoma­lies. According to discrimination diagrams such as Ti versus Zr (Pearce, 1983), the basalts were emplaced in a within­plate environment (Fig. 3). All these geochemical character­istics are typical of strongly fractionated intraplate tholeiitic basalts emplaced on continental crust.

The Katahdin volcanic rocks (Ripogenus Formation) also contain rift andesitic lava flows and dacitic porphyry plugs. The andesites have SiO₂ contents ranging from 54 to 58% and are distinct from calc-alkali equivalents in having higher contents of TiO₂ (1.8-1.9%) (Table 1). Their REE patterns are enriched in LREE with a flat HREE segment and La abundances about 70 x chondrites (Fig. 5). The shape of these REE profiles is similar to some basalt patterns. The basalts and andesites display continuous variation trends indicating that they are related and that fractional crystalliza­tion played an important role during their genesis. However, the differences between the basalts and andesites cannot be completely explained by a simple process of fractional crys­tallization and assimilation was probably an additional factor in their genesis.

The second type of mafic and intermediate rocks are represented solely by the andesites of the Edmunds Hill Formation. They have a relatively uniform composition with SiO₂ between 60 and 64% (Fig. 3), Mg # between 0.50 and 0.40. The abundances of incompatible trace elements are typical of those of subduction-related calc-alkali andesites erupted on relatively thin continental crust. The representa-
Fig. 4. Ti versus V diagram of Shervais (1982) for the Silurian-
Early Devonian basaltic rocks of the Piscataquis volcanic belts. The basalts have high Ti/V ratios typical of non-orogenic mag­
mas.

tive trace element abundances of andesitic lavas normalized
to the primitive mantle of Sun and McDonough (1989) (Fig.
6) display patterns with LILE enrichment and depletions in
HFSE, notably Nb and Ta, relative to LILE and LREE. Com­
pared to the patterns of the intraplate basalts (Fig. 6), the
andesites also have a negative Ti anomaly, characteristic of
arc magmas (Condie, 1987). The subduction-related charac­
ter of the andesitic rocks is also shown on the Ti-Zr discrimi­
nation plot (Fig. 3). The REE patterns are enriched in LREE,
show some HREE fractionation and have La/Yb ratios around
10 (Fig. 5).

DISCUSSION

Petrogenesis

The mafic extrusive rocks of the Silurian-Early De­
vonian Piscataquis volcanic belt are mainly intraplate tholeiitic
basalts that are variably but commonly highly fractionated.
Their composition is similar to many continental theleites
including those of the Chaleur and Dalhousie groups of the
Tobique belt of New Brunswick (Dostal et al., 1989). That
the rocks were derived from a compositionally heterogene­
ous mantle probably by a variable degree of melting is
indicated by (1) the variable abundances of incompatible
trace elements in basaltic rocks of a given Mg # with rela­
tively uniform major element compositions, and (2) differ­
ences in incompatible trace element ratios such as Zr/Y, La/
Yb and Zr/Nb. Their mantle-normalized incompatible trace
element patterns show a distinct enrichment of LILE relative
to HREE and HFSE accompanied by negative anomalies of
Nb and Ta. In contrast to typical arc samples (Condie, 1987),
the rocks do not show a negative Ti anomaly. The Nb-Ta
depletion that is frequently observed in continental theleites
probably represents compositional characteristics inherited
from the mantle source. The presence of Nb-Ta anomalies in
the mantle source might be due to the involvement of a crustal
component in the petrogenesis of the basalts and suggests a
subcontinental lithospheric source for the basalts. This
“crustal” signature may have been superimposed on the
mantle during the incorporation of crustal material into the
mantle by a pre-Silurian subduction process. Alternatively,
the Nb-Ta depletion could be due to crustal contamination of
basaltic magmas.

The andesites of the Edmunds Hill Formation are calc-
alkali and do not appear to be directly related to the tholeiitic basalts. The differences in the ratios of incompatible trace elements show that they were derived from a different source. The distribution of these elements is typical of subduction-related magma (Condie, 1987; Wilson, 1989).

Tectonic Significance

With the exception of the Edmunds Hill andesites, the Silurian-Early Devonian volcanism in the Piscataquis volcanic belt took place in an extensional setting rather than in a volcanic arc (e.g., Bradley, 1983); a similar conclusion to that obtained on the rocks from the Tobique volcanic belt (Dostal et al., 1989). Calc-alkali arc volcanism is limited spatially and temporally to late Early Devonian Edmunds Hill andesites in the Presque Isle area.

The Silurian-Early Devonian volcanic rocks are part of an Upper Ordovician-D Devonian sequence that oversteps cratonic North America and several accreted Ordovician terranes (Keppie, 1989). Their eruption overlaps the switch in the sedimentary source from northwest in the Silurian to predominant southeast in the Early Devonian (Hall et al., 1976; Osberg et al., 1989). The southeastern source is inferred to be the Avalon Composite Terrane and locally the Miramichi Highlands. Deposition of these rocks was synchronous with the sinistral accretion of the Avalon Composite Terrane to the eastern margin of the Appalachians (Keppie, 1989). The arrival of SE-derived flysch in the Early Devonian dates the initial accretion of the Avalon Composite Terrane to this part of the Appalachians. Dostal et al. (1989) argued that sinistral accretion of the Avalon Composite Terrane induced oblique extension in the Tobique volcanic belt and this model also appears to be applicable to the Piscataquis volcanic belt. The limited calc-alkali volcanism observed in the Edmunds Hill Formation may be explained by minor subduction at the end of the accretionary process (Keppie et al., 1991). This tectonic setting is generally similar to that envisaged by Laurent and Belanger (1984) and Bedard (1986) and is consistent with the Late Silurian-Early Devonian tectono thermal event associated with the accretion of the Avalon Composite Terrane recorded in the Miramichi Highlands of New Brunswick (van Staal et al., 1990) and in Newfoundland (Dunning et al., 1990).

Conclusions

The Silurian-Early Devonian basaltic rocks of the Piscataquis volcanic belt are mainly related to intracontinental crustal rifting. The volcanic rocks are bimodal with only minor amounts of intermediate rocks. The continental tholeiites were generated from a heterogeneous subcontinental lithospheric mantle source. The geochemical characteristics and genesis of most of these volcanic rocks are similar to those found in contemporaneous volcanism in the Tobique volcanic belt and in the Gaspé Peninsula (Laurent and Belanger, 1984; Bedard, 1986; Dostal et al., 1989). This rifting is inferred to have been caused by sinistral oblique accretion of the Avalon Composite Terrane to the North America craton (Keppie, 1989). During the terminal stages of accretion limited subduction took place to produce the aerially restricted calc-alkali volcanism in the Edmunds Hill Formation.

Acknowledgements

This study was partly supported by grants to R. Hon from the National Research Foundation of the United States of America and to J. Dostal from the Natural Sciences and Engineering Research Council of Canada. It is published with the permission of the Nova Scotia Department of Mines and Energy. We are grateful to the drafting section of the Nova Scotia Department of Mines and Energy. We are grateful to the drafting section of the Nova Scotia Department of Mines and Energy for preparation of the figures.

Condie, K.C. 1987. Early Proterozoic volcanic regimes in south-


