[AMERICAN JOURNAL OF SCIENCE, VOL. 281, MAY, 1981, P. 545-552]

ON THE TECTONIC SETTING OF ORDOVICIAN VOLCANIC ROCKS FROM NORTHERN MAINE

ANDREW HYNES

Department of Geological Sciences, McGill University,
3450 University Street, Montreal H3A 2A7, Canada

ABSTRACT. Immobile trace element data from Ordovician volcanic rocks of northern Maine reveal that the Winterville and Bluffer Pond Formations are similar to within-plate basalts, whereas the unnamed volcanics of the Island Falls and Stacyville quadrangles have characteristics of both within plate and island-arc basalts. However, the rocks are in many ways similar to high-titania, low-potash, alkalic island-arc rocks, for which no trace-element data are available. Some pyroxene analyses are available from such rocks, and they have characteristics similar to non-alkalic volcanic-arc basalts when plotted on the Nisbet and Pearce discriminant diagram. Using this information and plotting pyroxene data from northern Maine on the Nisbet and Pearce diagram, it can be shown that the Winterville and Bluffer Pond Formations probably were formed within a plate, on an oceanic island, whereas the unnamed volcanics of the Island Falls and Stacyville quadrangles probably originated in a volcanic arc.

INTRODUCTION

In an earlier paper (Hynes, 1976) the magmatic affinities of two suites of Ordovician volcanic rocks in northern Maine were described, using evidence from the compositions of relict pyroxenes. Both suites were assumed to have originated in volcanic arcs above subduction zones. Subsequent study of immobile trace element contents of these rocks indicates that one of the suites may have formed within a plate, in an oceanic island setting, although an island-arc setting is still possible. In this note the trace-element data are presented, and some of the problems with their interpretation are discussed. Support for the within-plate interpretation is provided by application of the discriminant function plot for pyroxene compositions developed by Nisbet and Pearce (1977).

GEOLOGY

The rocks concerned are from the Winterville and Bluffer Pond Formations and from unnamed volcanic formations in the Island Falls and Stacyville quadrangles of northern Maine. Details of the geology and major-element chemistry were given in the previous paper and will not be repeated here. The formations consist predominantly of mafic to intermediate metavolcanic rocks with greenschist facies mineral assemblages. All are of medial Ordovician age, and they were deposited in an area of volcanic islands which now lies just southeast of the Connecticut Valley-Gaspé synclinorium.

On the basis of petrographic appearance and the compositions of relict pyroxenes, the formations can be grouped into two suites. One, comprizing the Winterville and Bluffer Pond Formations, is bimodal. Mafic rocks in the suite contain titania-rich and silica-poor pyroxenes characteristic of silica-undersaturated basalts. The felsic rocks associated with them are quartz-bearing. The suite is probably the "straddle" type of alkalic suite as defined by Miyashiro (1978). The other suite, comprizing the unnamed volcanic rocks of the Island Falls and Stacyville quadrangles, contains many intermediate rock types as well as mafic and felsic

rocks. Pyroxenes in the more mafic rocks of this suite are silica-rich but are richer in diopside component than the pyroxenes typical of silica-saturated magmas. They have been interpreted as indicative of transitional magmatic affinity (Hynes, 1976). Rocks of both suites have high TiO_2 contents and high Na_2O/K_2O.

TRACE-ELEMENT CONTENTS

The trace elements discussed in this note (table 1) are some of those considered relatively immobile during metamorphism (for example,

TABLE 1
Trace element contents (ppm)*

	Winterville Formation							
	76A	77A	81B	79A	63A	69A	78A	81A
P	n.d.	3,204	3,558	1,749	n.d.	n.d.	n.d.	n.d.
Ti	19,700	21,200	18,600	10,400	18,300	16,700	17,000	12,100
Rb	2.0	n.d.	n.d.	n.d.	7.6	n.d.	5.0	6.4
Sr	281	197	210	208	517	345	468	160
Y	15	17	23	19	19	26	16	23
Zr	169	132	126	102	172	158	161	114
Nb	n.d.	28	11	3.9	28	28	22	42
Y/Nb	n.d.	0.61	2.1	4.9	0.68	0.93	0.73	0.55

	Bluffer Pond Formation				
	93B	99B	86A	90B	96A
P	n.d.	1,257	n.d.	n.d.	n.d.
Ti	10,400	10,600	9,170	19,400	15,600
Rb	1.0	n.d.	14	14	9.2
Sr	224	147	161	139	276
Y	18	12	24	31	25
Zr	105	18	146	190	212
Nb	17	21	17	18	17
Y/Nb	1.1	0.57	1.4	1.7	1.5

	Unnamed volcanics, Stacyville quadrangle				
Rock	14B	2B	16C	19A	17A
P	948	2,011	n.d.	n.d.	n.d.
Ti	6,000	7,910	6,530	10,900	9,290
Rb	n.d.	n.d.	1.0	1.8	2.6
Sr	98	126	55	63	23
Y	17	20	20	18	21
Zr	67	77	74	76	75
Nb	12	14	8.4	n.d.	5.0
Y/Nb	1.4	1.4	2.4	n.d.	4.2

	Unnamed volcanics, Island Falls quadrangle						
Rock	35A	24A	24B	41A	42A	49A	34B
P	1,468	2,009	n.d.	n.d.	891	1,039	n.d.
Ti	11,300	10,800	12,200	16,200	5,580	6,770	3,900
Rb	n.d.	n.d.	n.d.	14	n.d.	n.d.	44
Sr	42	44	47	115	114	156	130
Y	20	21	18	19	22	20	19
Zr	88	78	75	206	71	94	62
Nb	7.7	16	20	25	11	19	23
Y/Nb	2.6	1.3	0.90	0.76	2.0	1.1	0.83

* Rock numbers are the same as in Hynes (1976). Analyses were by XRF using a Philips model PW1220 semiautomatic spectrometer and the method of Webber and Newbury (1971). n.d. = not determined.

Cann, 1970; Winchester and Floyd, 1976). Although the postulated universal immobility of these trace-elements has been questioned (Vallance, 1974) it can be demonstrated in many cases (for example, Winchester and Floyd, 1976; Smith and Smith, 1976; Morrison, 1978), and it appears to be a reasonable starting assumption.

The rocks are consistently high in Nb. In addition the Y/Nb ratios are low. These features are characteristic of transitional to undersaturated rocks (Pearce and Cann, 1973), and the relative values of Y/Nb for the two suites suggest that the Winterville-Bluffer Pond suite is more undersaturated than the Island Falls-Stacyville suite, in good agreement with deductions from relict pyroxene compositions (Hynes, 1976).

In this study Pearce and Cann's (1973) Ti–Y–Zr diagram (fig. 1) is used to suggest tectonic settings for the volcanic rocks. Morrison (1978) has criticized the use of this diagram, since data from the Hebridean province yield results spanning several different "tectonic" fields on the diagram, and some even fall within the calc–alkalic (volcanic arc) field which is clearly incompatible with the known tectonic environment of the rocks. As discussed by Morrison the high Zr/Ti reflected in rocks assigned to the calc–alkalic field may well be due to fractionation effects

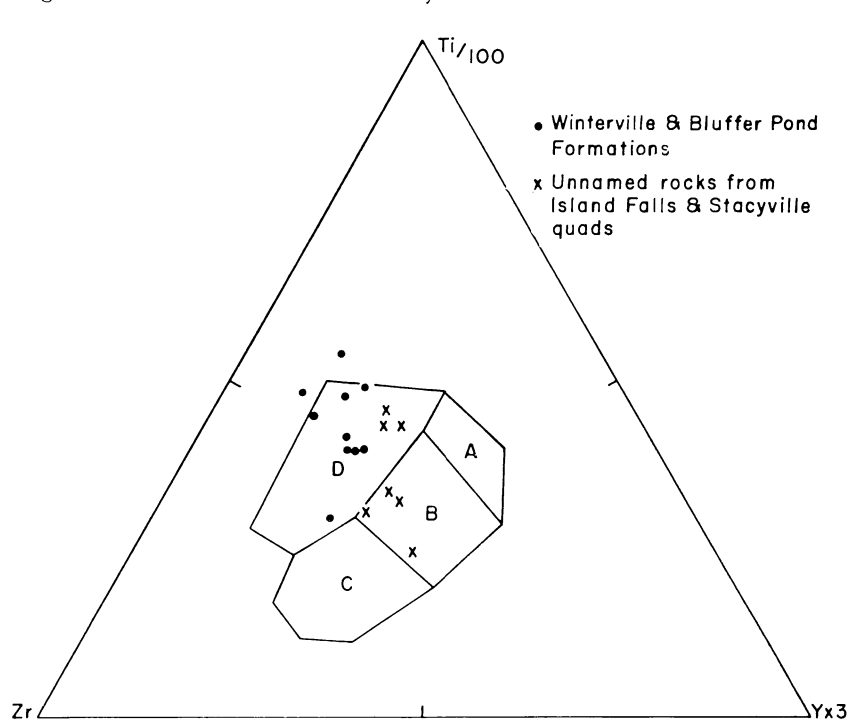

Fig. 1. Analyses from northern Maine on Ti–Y–Zr discrimination diagram after Pearce and Cann (1973). A = low-potassium tholeiites; B = low potassium tholeiites, ocean floor basalts, and calc–alkali basalts; C = calc–alkali basalts; D = "within plate" basalts. Data from table 1 are plotted only if they satisfy Pearce and Cann's criterion that $12 < CaO + MgO < 20$ wt percent.

not recognizable using the major element screening criteria recommended by Pearce and Cann (1973). Since the analyses from Maine have relatively low Zr/Ti this is unlikely to be a problem in the present study. The other analyses presented by Morrison fall in the "within-plate" and "ocean-floor basalt" fields both of which appear to be compatible with the tectonic environment in the Hebrides. While there is no doubt that the scheme of Pearce and Cann is not perfect, it remains a valuable, if entirely empirical, discriminatory tool for the tectonic setting of mafic volcanic rocks.

Rocks from the Winterville-Bluffer Pond suite fall in the "within-plate basalts" field, whereas those from the Island Falls-Stacyville suite span the boundary between this field and a field containing representatives of low K tholeiites, ocean-floor basalts, and calc–alkalic basalts. The diagrams cannot, however, be simply interpreted, because in setting up their diagram Pearce and Cann excluded from consideration undersaturated rocks occurring in island arcs. Since the northern Maine rocks are known to be transitional or undersaturated this possible tectonic setting must also be considered, and some review of the rocks in the setting is necessary.

Since the work of Chayes (1964) and Chayes and Velde (1965) it has been widely accepted that volcanic-arc rocks are low in titania. In some cases this applies to the alkalic rocks as well as the more common types. Kesson and Smith (1972) noted that the shoshonitic (K_2O-rich, alkalic) association of island arcs contains rocks with generally less than 1.3 wt percent TiO_2, whereas the "alkaline association proper" of oceanic islands, continental margins, and rift systems contains rocks with higher TiO_2. However, shoshonitic rocks are not the only alkalic types that occur in island arcs (Miyashiro, 1975), and many of the more sodic alkalic rocks are much richer in titania than island-arc rocks. Titania-rich ($TiO_2 > 2$ wt percent) alkalic basalts with K_2O/Na_2O less than 0.5 occur in several parts of the Japanese islands (Aoki, 1959; Kuno, 1960; Tiba, 1966; Uchimuzu, 1966), in the Kuriles (Yagi, 1969) in the Aleutians Hoare and others, 1968), and in the Pribilof islands (Barth, 1956). Although many of these occurrences may reflect unusual tectonic developments (DeLong, Hodges, and Arculus, 1975), they must be regarded as not uncommon in island arcs, and there is the distinct possibility that the high TiO_2, low K_2O rocks of northern Maine were formed in this setting.

Trace-element data for the alkalic rocks of island arcs are not abundant. Rocks from the shoshonite association of Fiji (Gill, 1970) and from low K_2O alkalic rocks of the Lesser Antilles (Siggurdsson and others, 1973; Arculus, 1976) fall in the "calc–alkalic" field of Pearce and Cann's Ti–Y–Zr plot, but both suites have low titania and are not directly comparable with the suites in Maine. Trace element data from the high titania, alkalic rocks of island arcs are unknown to the writer.

From trace-element data alone then, no choice can be made for the tectonic setting of the Winterville-Bluffer Pond suite. It could have

originated within a plate, but an island arc-origin cannot be ruled out. For the Island Falls-Stacyville suite the spread of data into a low titanium field makes a within-plate origin doubtful and suggests that an island-arc origin is more probable, but again no clear choice is possible.

DISCRIMINATION WITH PYROXENE COMPOSITION

Further indications can be derived from the major-element compositions of pyroxenes in the rocks. Nisbet and Pearce (1977) developed a method for discrimination of tectonic setting using analyses from the pyroxenes in basaltic rocks. Their system has the advantage that problems of chemical mobility are reduced but the disadvantage that the discrimination is not as effective as that using immobile trace elements. However, an added advantage for this study is that there are pyroxene compositional data from some of the high-titania alkalic basalts of island arcs, notably from Japan. These were not included in Nisbet and Pearce's compilation, but figure 2 shows that available pyroxene-data from the

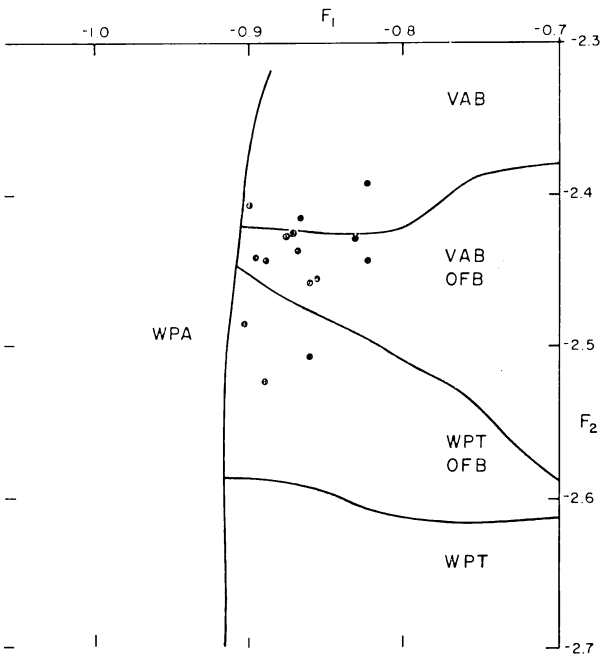

Fig. 2. Clinopyroxene compositions in mafic rocks from alkalic suites of Japan plotted on the discriminant diagram of Nisbet and Pearce (1977). VAB = volcanic arc basalts; OFB = ocean-floor basalts; WPT = within plate tholeiites; WPA = within plate alkalic basalts.

$F_1 = -0.012SiO_2 - 0.0807TiO_2 + 0.0026Al_2O_3 - 0.0012FeO^* - 0.0026MnO + 0.0087MgO - 0.0128CaO - 0.0419Na_2O.$

$F_2 = -0.0469SiO_2 - 0.0818TiO_2 - 0.0212Al_2O_3 - 0.0041FeO - 0.1435MnO - 0.0029MgO + 0.0085CaO + 0.0160Na_2O.$

Data are from Aoki (1964), Tiba (1966), and Uchimuzu (1966). Only pyroxenes from mafic volcanic rocks (referred to as "basalts" or "alkali basalts" by the authors) are plotted.

high-titania alkalic rocks of Japan generally fall in or near the volcanic arc basalts fields defined by Nisbet and Pearce using only non-alkalic rocks. Their scheme therefore provides a tentative way in which to discriminate between within-plate alkalic rocks and island-arc alkalic rocks.

The pyroxene-data from rocks in Maine, previously used to determine magmatic affinity (Hynes, 1976) show clearly (fig. 3) that the rocks of the Winterville-Bluffer Pond suite have the general characteristics of within plate basalts, not volcanic arc basalts. Analyses from the Island Falls-Stacyville suite are more typical of volcanic arc basalts and support the tentative conclusion drawn from the trace-element data that it originated in an island-arc.

CONCLUSIONS

All available data indicate that the rocks of the Winterville-Bluffer Pond suite are undersaturated in nature. Trace element contents are compatible with either a within plate origin (seamount or within continent) or an island-arc origin. Since field relationships show a clearly oceanic setting the most probable within-plate origin for the rocks would be on an oceanic island or seamount. Pyroxene data from the rocks favor

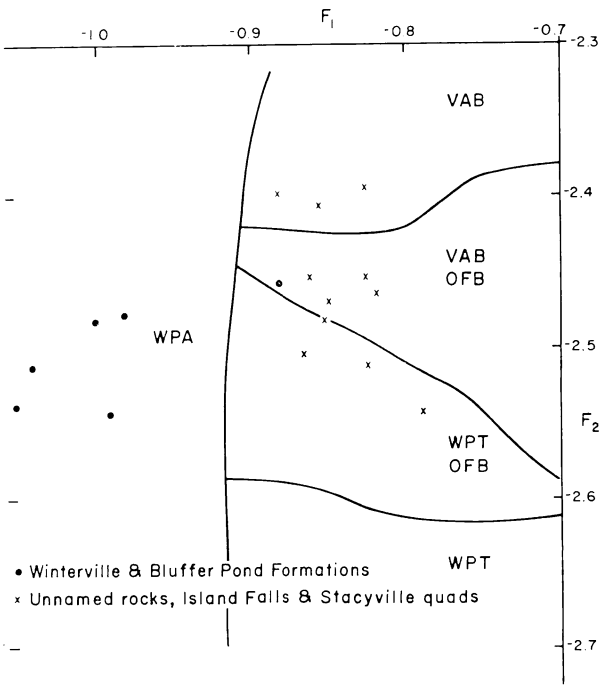

Fig. 3. Clinopyroxene compositions from mafic rocks of northern Maine plotted on the same diagram as figure 2. Each point represents the average of several analyses from one rock.

a within-plate origin over an island-arc origin. The rocks of the Island Falls-Stacyville suite are transitional to alkalic in nature. Trace element contents make a within-plate origin difficult, and pyroxene compositions are generally compatible with origin in an island arc. The excursion into the "within-plate" field on Pearce and Cann's diagram may be a reflection of the alkalic nature of the rocks. These conclusions must be regarded as tentative, given the limited data available on the alkalic rocks of island arcs.

ACKNOWLEDGMENTS

This research was supported by the National Research Council of Canada. I am grateful to Barry Doolan whose manipulations of my pyroxene analyses using a different, as yet unpublished, scheme spurred me to write this.

REFERENCES

Aoki, K., 1959, Petrology of alkali rocks of the Iki Islands and the Higashimatsuura District, Japan: Tohoku Univ. Sci. Repts., ser. III, v. 6, p. 261-310.

———— 1964, Clinopyroxenes from alkaline rocks of Japan: Am. Mineralogist, v. 49, p. 1199-1223.

Arculus, R. J., 1976, Geology and geochemistry of the alkali basalt–andesite association of Grenada, Lesser Antilles island arc: Geol. Soc. America Bull., v. 87, p. 612-624.

Barth, T. F. W., 1956, Geology and petrology of the Pribilof Islands, Alaska: U.S. Geol. Survey Bull. 1028-F, 160 p.

Cann, J. R., 1970, Rb, Sr, Y, Zr and Nb in some ocean floor basaltic rocks: Earth Planetary Sci. Letters, v. 10, p. 7-11.

Chayes, F., 1964, A petrographic distinction between Cenozoic volcanics in and around the open oceans: Jour. Geophys. Research, v. 69, p. 1573-1588.

Chayes, Felix and Velde, D., 1965, On distinguishing basaltic lavas of circumoceanic and oceanic-island type by means of discriminant functions: Am. Jour. Sci., v. 263, p. 206-222.

DeLong, S. E., Hodges, F. N., and Arculus, R. J., 1975, Ultramafic and mafic inclusions, Kanaga Island, Alaska, and the occurrence of alkaline rocks in island arcs. Jour. Geology, v. 83, p. 721-736.

Gill, J. B., 1970, Geochemistry of Viti Levu, Fiji, and its evolution as an island arc: Contr. Mineralogy Petrology, v. 27, p. 179-203.

Hoare, J. M., Condon, W. H., Cox, A., and Dalrymple, G. R., 1968, Geology, paleomagnetism and potassium-argon ages of basalts from Nunivak Island, Alaska: Geol. Soc. America Mem. 116, p. 377-412.

Hynes, Andrew, 1976, Magmatic affinity of Ordovician volcanic rocks in northern Maine and their tectonic significance: Am. Jour. Sci., v. 276, p. 1208-1224.

Kesson, S. E., and Smith, I. E., 1972, TiO_2 content and the shoshonite and alkaline associations: Nature Phys. Sci., v. 236, p. 110-111

Kuno, H., 1960, High-alumina basalt: Jour Petrology, v. 1, p. 121-145.

Miyashiro, A., 1975, Island arc volcanic rock series: a critical review: Pétrologie, v. 1, p. 177-187.

———— 1978, Nature of alkalic volcanic rock series: Contr. Mineralogy Petrology, v. 66, p. 91-104.

Morrison, M. A., 1978, The use of 'immobile' trace elements to distinguish the palaeotectonic affinities of metabasalts: applications to the Paleocene basalts of Mull and Skye, northwest Scotland: Earth Planetary Sci. Letters, v. 39, p. 407-416.

Nisbet, E. G., and Pearce, J. A., 1977, Clinopyroxene composition in mafic lavas from different tectonic settings: Contr. Mineralogy Petrology, v. 63, p. 149-160.

Pearce, J. A., and Cann, J. R., 1973, Tectonic setting of basic volcanic rocks determined using trace element analyses: Earth Planetary Sci. Letters, v. 19, p. 209-300.

Sigurdsson, H., Tomblin, J. F., Brown, G. M., Holland, J. G., and Arculus, R. J., 1973, Strongly undersaturated magmas in the Lesser Antilles island arc: Earth Planetary Sci. Letters, v. 18, p. 285-295.

Smith, R. E., and Smith, S. E., 1976, Comments on the use of Ti, Zr, Y, Sr, K, P and Nb in classification of basaltic magmas: Earth Planetary Sci. Letters, v. 32, p. 114-120.

Tiba, T., 1966, Petrology of the alkaline rocks of the Takakusayama District, Japan: Tohoku Univ. Sci. Repts., ser. III, p. 541-510.

Uchimizu, M., 1966, Geology and petrology of alkali rocks from Dogo, Oki Island: Univ. Tokyo Fac. Sci. Jour., ser. II, v. 16, p. 85-159.

Vallance, T. G., 1974, Spilitic degradation of a tholeiitic basalt: Jour. Petrology, v. 15, p. 79-96.

Webber, G. R., and Newbury, M. L., 1971, X-Ray fluorescence determination of minor and trace elements in silicate rocks: Canadian Spectroscopy, v. 16, p. 90-93.

Winchester, J. A., and Floyd, P. A., 1976, Geochemical magma type discrimination: application to altered and metamorphosed basic igneous rocks: Earth Planetary Sci. Letters, v. 28, p. 459-469.

Yagi, K., 1969, Petrology of the alkalic dolerites of the Nemuro peninsula, Japan: Geol. Soc. America Mem. 115, p. 103-147.