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FROM CONTINENTS TO ISLAND ARCS: A GEOCHEMICAL INDEX OF TECTONIC SETTING FOR ARC-RELATED AND WITHIN-PLATE FELSIC TO INTERMEDIATE VOLCANIC ROCKS

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Abstract

Three distinct tectonic regimes were identified for felsic and intermediate volcanic rocks using published datasets from twenty-six different geographical locations around the world. The three well-defined tectonic regimes include oceanic arcs, active continental margins and within-plate volcanic zones. This subdivision is based on concentrations and ratios of the incompatible trace elements Ta, Th and Yb as geochemical tectonic discriminants. The separation of tectonic regimes is demonstrated on two discriminant diagrams, where the three zones are separated by *ca.* 45° diagonal lines on one, and by horizontal lines on the other. The *ca.* 45° trends of the boundaries between tectonic provinces on a Ta/Yb *versus* Th/Yb diagram are due to the similar incompatibility of Th and Ta relative to the somewhat lower incompatibility of Yb. On a Th/Ta *versus* Yb diagram, the three tectonic zones are separated by horizontal lines; datasets within individual zones have characteristic Th/Ta values, *ca.* 1–6 for within-plate volcanic zones, >6–20 for active continental margins, and >20–90 for oceanic arcs. These discriminant diagrams can be successfully used to identify the tectonic environments of intermediate and felsic volcanic rocks , and to evaluate the tectonic history of a region.

Keywords: geochemical discriminant, felsic–intermediate volcanic rocks, oceanic arcs, active continental margins, within-plate volcanic zones.

Sommaire

Trois milieux tectoniques distincts de volcanisme felsique et intermédiaire ont été identifiés en utilisant des données publiées décrivant vingt-six localités géographiques différentes sur une échelle mondiale. Les trois régimes tectoniques sont: arcs océaniques, marges continentales actives et zones volcaniques intra-plaques. Cette subdivision est fondée sur les concentrations et les rapports des éléments traces incompatibles Ta, Th et Yb. La distinction des régimes tectoniques se fait au moyen de deux diagrammes, dans lesquels les trois zones sont séparées par des lignes diagonales ayant une pente d'environ 45° et par des lignes horizontales, respectivement. Les lignes limitrophes à pente de 45° entre provinces tectoniques sur un diagramme de Ta/Yb *versus* Th/Yb témoignent de l'incompatibilité semblable de Th et de Ta, et de l'incompatibilité relativement plus faible de l'ytterbium. Sur un diagramme montrant Th/Ta *versus* Yb, les trois zones tectoniques sont délimitées par des lignes horizontales. Les groupes de données à l'intérieur des domaines possèdent des valeurs de Th/Ta caractéristiques: environ 1–6 pour les suites volcaniques intra-plaques, entre 6 et 20 pour les suites typiques des marges continentales actives, et au delà de 20 jusqu'à 90 pour les suites provenant d'arcs océaniques. Nous avons appliqué ces diagrammes avec succès pour identifier le milieu tectonique de formation de roches volcaniques intermédiaires et felsiques, et pour évaluer l'évolution tectonique d'une région.

(Traduit par la Rédaction)

Mots-clés: discrimination géochimique, roches volcaniques felsiques et intermédiaires, arcs océaniques, marges continentales actives, zones volcaniques intra-plaques.

Introduction

Discriminant diagrams have been successfully used in the past to identify the tectonic environments of ancient and modern *mafic* igneous rocks (*cf.* Pearce 1982, 1983, 1996, Pearce & Peate 1995, Winchester & Floyd 1977, Winchester *et al.* 1992, Wood 1980). These diagrams are based on the empirical observations that there are systematic chemical differences in the source characteristics of basic magmas erupted in different tectonic settings. Thus the concentrations and ratios of selected elements can be used to distinguish among these tec-

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tonic settings. Our objective in the present paper is to define the tectonic fields of intermediate and felsic volcanic rocks on discriminant diagrams by using trace-element ratios of recent volcanic rocks from well-known tectonic terranes. Once these fields are established, the diagrams can be used to determine the tectonic evolution of the area, and they can be applied to rocks from ancient environments even though the primary geochemistry has been modified by metamorphism and hydrothermal alteration.

Previous Work

High field-strength elements (*HFSE*) such as Ta and Th are commonly used to identify tectonic environments of basaltic rocks. Basalts from subduction zones were found to be preferentially enriched in Th with respect to Ta (Pearce & Peate 1995), whereas within-plate basalts (WPB) and basalts from mid-oceanic ridges (MORB) were found to show no such enrichment. Thus on a Ta/Yb – Th/Yb diagram, WPB and MORB lie in a well-defined zone having a slope of about 1, and basalts derived from subduction zones form a roughly vertical trend. Recent work by Hawkesworth *et al.* (1991, 1993, 1997), Pearce & Parkinson (1993), Pearce & Peate (1995), and Pearce *et al.* (1995) has demonstrated that the chemical composition of volcanic rocks in subduction zones reflects the contribution of various components such as mantle wedge, oceanic crust, sediments, fluids and hydrous melts to magmas generated by subduction. Because subduction zones have a distinct geochemical signature, trace and rare-earth elements (*REE*) and radiogenic isotopes are commonly used in petrogenetic studies to identify and quantify the contribution of these components to arc rocks (*cf.* Hawkesworth *et al.* 1991, 1993, Pearce *et al.* 1992, 1995). Most arc-derived rocks have higher *LREE*/*HFSE* and *LILE*/*HFSE* values (*LREE*: light rare-earth elements; *LILE*: large-ion lithophile elements) than rocks crystallized from mantle-derived melts in other tectonic settings (*cf.* Hawkesworth *et al.* 1993), and these consistently higher values are attributed to the introduction of hydrous fluid into the mantle-wedge source (Tatsumi *et al.* 1995) and to scavenging of elements by fluids from the mantle wedge (Le Bel *et al.* 1985, Arculus & Powell 1986, Hawkesworth *et al.* 1991). The fluid derived by dehydration of subducting oceanic crust plays an important role in element transfer between the slab and arc-generated magmas. Pearce & Peate (1995) distinguished between "conservative" elements (*HFSE* and the heavy rare-earth elements, *HREE*), which are unaffected by the downgoing slab, and "nonconservative" elements (*LILE* and *LREE*), which are significantly affected. They suggested that the *HFSE* and *HREE* are left behind in the subducted slab because they are contained in discrete accessory phases, or because they are not mobilized by fluids, whereas *LILE* and *LREE* are incorporated into the subduction-generated magma *via* melting or *via* aqueous fluids (dehydration). There are some exceptions to the above, however. For example, Th is a *HFSE*, but it behaves as a nonconversative element in arc environments (Pearce & Peate 1995). Because the solubility of Th in subduction-zone fluids is extremely low (Bailey & Ragnasdottir 1994), the element is considered to be derived from the sediment component of the downgoing slab. This inference would explain the well-documented increase of Th with respect to Ta in arc magmas (Hawkesworth *et al.* 1997). Although the exact mechanism responsible for the enrichment of Th with respect to Ta in arc magmas is controversial (*i.e.*, a higher partition coefficient for Th, or the retention of Ta-rich accessory phases in the slab), the fact remains that arc-generated magmas have a higher Th:Ta ratio than magmas generated in within-plate volcanic zones.

Some *REE* have been successfully used as tectonic discriminants in mafic rocks. Hawkesworth *et al.* (1991, 1993) demonstrated that as the *REE* generally form a coherent series, island-arc basalts and continental-margin basalts may be distinguished by their Ce/Yb values where the rocks contain ≥53 wt% SiO_2. Cerium is a "nonconservative" element, and Yb behaves "conservatively" (Pearce & Peate 1995). Although the Ce:Yb ratio is a useful discriminant for mafic rocks, the pattern of behavior of these elements is less well established for intermediate and felsic rocks.

Petrogenetic studies by Defant & Drummond (1990, 1993) demonstrate the complexity of intermediate and felsic volcanic rocks in subduction zones. They suggested that some arc-related felsic magmas are generated by the partial melting of young subducted, hot oceanic crust at the depth of amphibolite–eclogite transition (Defant & Drummond 1990, 1993), where the source region is characterized by the presence of residual garnet and the absence of plagioclase (Defant & Drummond 1990). The rocks derived from these magmas are known as adakites and have a unique geochemical signature: high Al (>15 wt% Al_2O_3) and Sr (>400 ppm), low *HREE* (Yb < 1.9 ppm) and Y (<18 ppm) concentrations, and high Sr:Y ratio (>40) (Defant & Drummond 1990, 1993).

Analytical Techniques

Datasets presented on the diagrams in this paper (with the exception of the San Nicolas samples) are from the published works of authors cited in the figure captions. Most Ta, Th and Yb data were obtained by instrumental neutron-activation analysis (INAA) and, in some of the more recent papers, by inductively coupled plasma – mass spectrometry (ICP–MS). For a detailed description of the analytical procedures, the reader is referred to the individual papers. The San Nicolas samples (Mexico) were analyzed by the authors (INAA) at the University of Toronto (Appendix 1).

It is important to note here that owing to the low concentrations of Ta and Th in some rocks, high-quality data are essential if the diagrams presented in this paper are to be used. Sample preparation is particularly important, as at low Ta concentrations (<1 ppm), samples crushed in a tungsten carbide mill are liable to give erroneous results because of significant but variable Ta contamination.

Discriminant Diagrams for Arc-Related and Within-Plate Felsic to Intermediate Volcanic Rocks

The nonconservative behavior of Th in arc environments makes this element an ideal index to distinguish among different tectonic zones. Thus we demonstrate the application of a modified Ta/Yb – Th/Yb diagram (after Pearce 1983), and a new Th/Ta – Yb diagram to define distinct tectonic zones for intermediate and felsic volcanic rocks.

Ta/Yb – Th/Yb plots were constructed on the basis of geochemical data obtained from several suites of intermediate and felsic volcanic rocks representing a wide variety of geographic locations. Intermediate rocks cover the SiO_2 ranges from 54 to <63 wt% and MgO, from 3.0 to 4.5 wt%. Felsic rocks are defined as those having SiO_2 in the range 63 to 77 wt% and MgO in the range 0–2.0 wt%. Figures 1 and 2 demonstrate that the

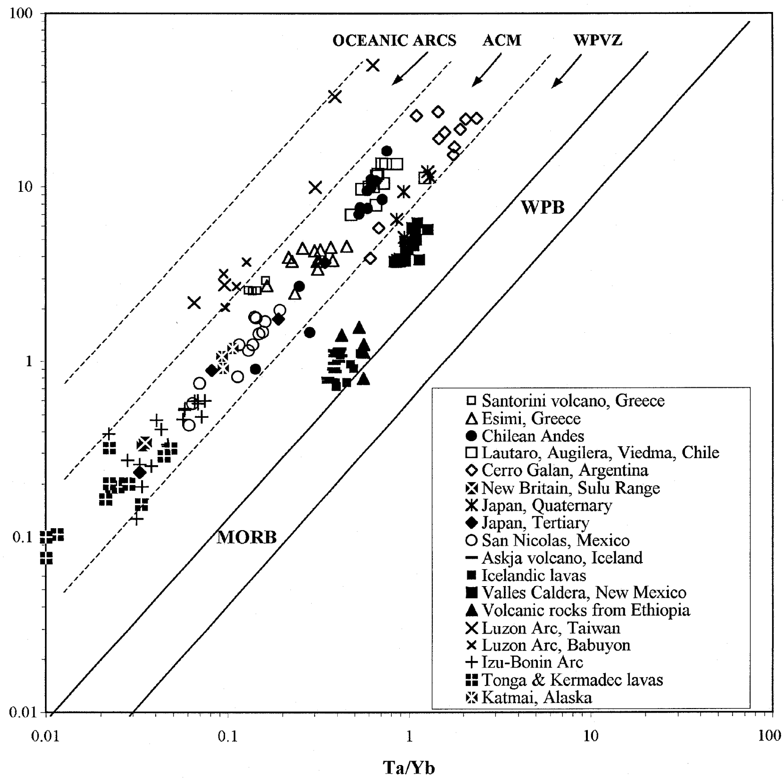

FIG. 1. The revised Th/Yb – Ta/Yb diagram (after Pearce 1982, 1983) is divided into three tectonic fields: oceanic arcs, active continental margins (ACM) and within-plate volcanic zones (WPVZ). The within-plate basalts (WPB) and MORB (mid-ocean ridge basalts) represent the zones previously defined by Pearce (1982, 1983). Datasets shown by various symbols include the Valley of Ten Thousand Smokes, Katmai, Alaska (Hildreth 1981), Santorini volcano (Mann 1983), Esimi volcanic suite (Lasthiotakis 1994), Chilean Andes (Rogers & Hawkesworth 1989, Davidson *et al.* 1990), Lautaro, Augilera and Viedma, Chile (Stern & Kilian 1996), Cerro Galan, Argentina (Francis *et al.* 1989), Tonga and Kermadec lavas (Ewart *et al.* 1998, Turner *et al.* 1997), New Britain Island Arc (Woodhead *et al.* 1998), Japan (Morris 1995, Ebihara *et al.* 1984), San Nicolas, Mexico (Schandl & Gorton, unpubl. data; see Appendix 1), Askja volcano and Icelandic lavas (Macdonald *et al.* 1988, Wood, 1978), Valles caldera, New Mexico (Spell *et al.* 1993), volcanic rocks from Ethiopia (Walter *et al.* 1987), the Luzon Arc (Defant *et al.* 1990) and the Izu–Babuyon Forearc.

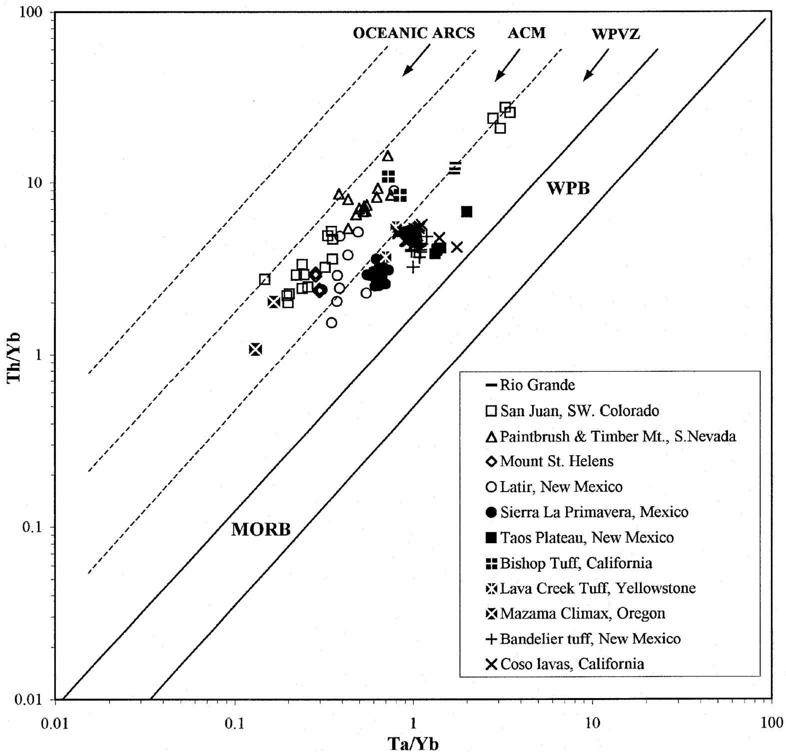

FIG. 2. Revised Ta/Yb – Th/Yb discriminant diagram (after Pearce 1983). Several datasets are from Lipman (1987); Rio Grande, San Juan, southwestern Colorado, Paintbrush and Timber Mountains, southern Nevada, Latir New Mexico, and Taos Plateau, New Mexico. Other datasets include the Bandelier Tuffs, New Mexico (Stix & Gorton 1993), Sierra La Primavera, Mexico (Mahood 1981), Coso lavas, California (Bacon *et al.* 1981), Bishop Tuff, California (Hildreth 1981), Mount St. Helens (Lipman *et al.* 1981), Lava Creek Tuff (Hildreth 1981), and Mazama Climax, Oregon (Hildreth 1981).

volcanic suites show specific geochemical trends in the three well-defined tectonic environments, namely, oceanic arcs, active continental margins (ACM) and within-plate volcanic zones (WPVZ). Figure 1 shows a compilation of data from vastly different geographic locations (Iceland, Greece, Australia, Ethiopia, Chile, Argentina, Philippines, New Britain, Tonga and Kermadec Islands, Japan, U.S. and Mexico). The sources of data are listed in the caption to Figure 1. Figure 2 is a compilation of data from the western part of the United States, with sources also listed in the caption.

Datasets plotted on the discriminant diagrams define three tectonic zones separated by stippled lines drawn on the basis of the suites collected from specific tectonic regimes. Rocks erupting in within-plate volcanic zones (WPVZ) have the lowest Th/Ta values (1–6), active continental margins (ACM) have intermediate values (>6–20), and the highest Th/Ta values occur in rocks erupting in oceanic arcs (>20–90). The separation of oceanic arcs and active continental margins by the *ca.* 45° lines on Figure 1 is different from that in Pearce's diagram, where a vertical division between oceanic arcs and continental margins is placed at Ta/Yb = 0.1 (Pearce 1983, his Fig. 9). We suggest that the progressive enrichment in Th in the three sequential environments on Figure 1 (WPVZ, ACM and oceanic arcs) reflects the increasing contribution of an arc component to the erupting lavas. It is evident from Figures 1 and 2 that within a cogenetic suite, the increase in Th/Yb is accompanied by a comparable increase in Ta/Yb (*i.e.*, Fig. 1: Luzon Arc, San Nicolas, Esimi, Greece, Cerro Galan, Argentina, Izu-Bonin Arc, and Fig. 2: San Juan, Colorado). This proportional increase in the intermediate and felsic rocks can be explained by the fact that Th and Ta are quite similar with respect to their degree of incompatibility, whereas Yb is significantly less incompatible. In rhyolitic rocks, Ta and Th may no longer be completely incompatible once accessory minerals have crystallized; the key factor, however, is the difference in incompatibility between Ta and Th on one hand, and Yb on the other. It is to be expected that within a suite, Th and Ta will be enriched relative to Yb to about the same degree during magmatic processes, creating the observed *ca.* 45° trends. Thus, the boundaries between tectonic provinces should parallel these trends.

The datasets on Figure 1 demonstrate the clear-cut separation between the three tectonic provinces. Rocks from Iceland, Ethiopia and Valles Caldera, New Mexico plot in the within-plate volcanic zone; rocks from Greece, Chile, Argentina, Japan, Mexico, Alaska, and the Tonga–Kermadec and Izu–Bonin arcs plot on the active continental margin zone, and rocks from the Luzon arc plot on the zone of oceanic arcs. It is apparent that the separation of these tectonic zones is dependent on Th, Ta and Yb concentrations and ratios. If the ratios are modified, data points may be offset to an adjacent zone. This was observed in the dataset from the Izu–Bonin Forearc, where isotopic evidence suggests that the lavas, which range from boninite to andesite – dacite – rhyolite, consist of three components: (1) depleted Pacific MORB mantle, (2) volcanogenic sediments, and (3) subducted fluids (Pearce *et al.* 1992). The extremely low Th concentration in the Izu–Bonin arc rocks is consistent with the addition of a depleted MORB component, and thus, the displacement of datapoints into the ACM field. A similar displacement is seen for the Tonga–Kermadec dataset, reflecting the complexity of the area. The Tonga–Kermadec arc contains an active continental-margin environment such as New Zealand. The abundance of dacitic and rhyolitic rocks in the arc would suggest that its affinities lie more with ACM rocks than with intra-oceanic rocks. The Tonga–Kermadec arc was split by back-arc rifting, and the subsequent subsidence gives the false impression of an intra-oceanic arc. The displacement of the Izu–Bonin and Tonga–Kermadec datasets to the zone of ACM on Figure 1 suggests that the position of the datasets on the diagram are influenced by the tectonic and geochemical evolution of the area.

Figures 3 and 4 are self-explanatory; rocks from the Luzon oceanic arc plot in the oceanic arc field, the subduction-related rocks (see Figs. 1 and 2) plot in the ACM field, and rocks from within plates plot in the WPVZ field of the diagrams. Although the data points in Figures 1 and 2 represent different geographical locations, a strong *ca.* 45° trend is evident within the same suites in Figures 1 and 2, and a strong vertical trend on Figures 3 and 4.

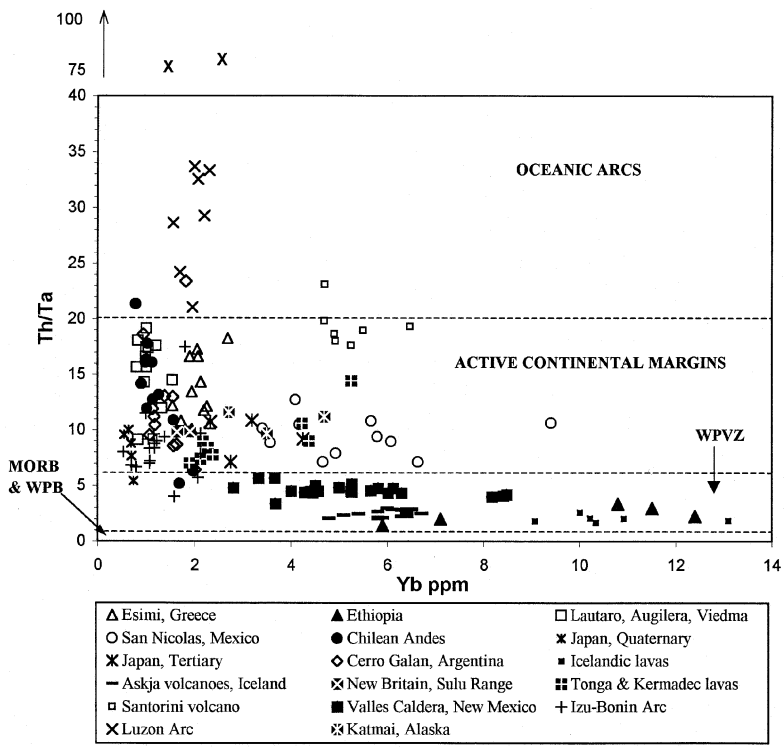

FIG. 3. Th/Ta – Yb discriminant diagram. The three tectonic zones defined are taken from Figure 1. Datasets are the same as in Figure 1.

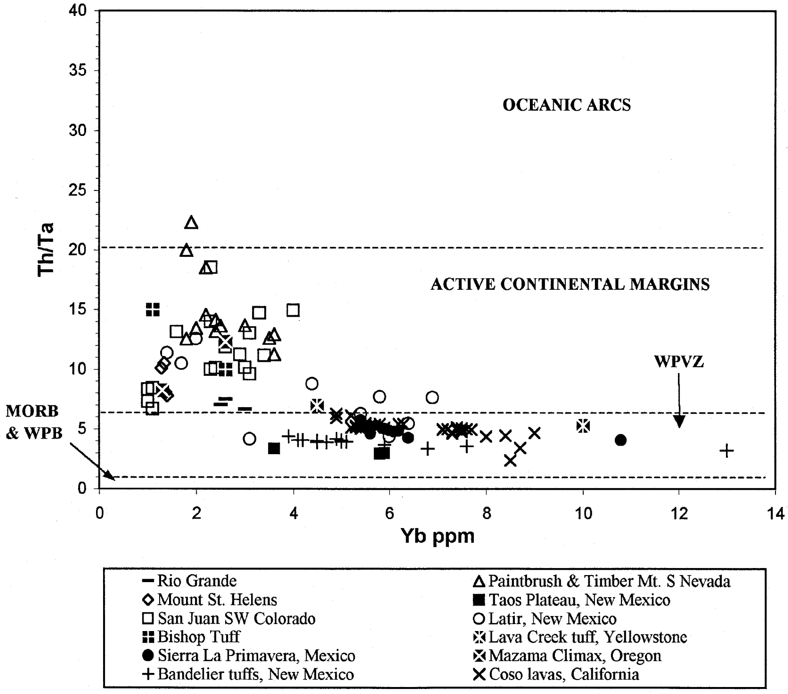

FIG. 4. Th/Ta – Yb discriminant diagram. Datasets are the same as in Figure 2.

There is no clear-cut separation between rocks with chemical characteristics of adakites (Lautaro, Viedma, Augilera, Chilean Andes and the Quaternary volcanic rocks of Japan) and other subduction-related volcanic rocks. There is a tendency, however, for adakites to plot at the higher end of the Th/Yb axis. This is not so much a function of Th enrichment, but the low Yb concentration in these rocks (Fig. 3).

Although there is good spatial separation between volcanic rocks of different tectonic environments on Figures 1 and 2, there is some overlap between the ACM and the WPVZ fields on Figure 2. The datasets that span the two tectonic fields represent rocks from the western part of the United States, including the southern Rocky Mountains and adjacent areas. Such overlap may be explained by the fact that the geochemistry of rhyolitic rocks is strongly influenced by the geochemistry of their source rocks. Thus a significant crustal component will move the data points across the ACM–WPVZ boundary. Data points on Figure 2 reflect the tectonic complexity of the region, which has evolved from low-angle subduction to an extensional environment. The transition from subduction- to extension-related volcanism in the area began *ca.* 26 m.y. ago (*cf.* Lipman 1987). Volcanic suites associated with mid-Tertiary low-angle subduction include rocks from the San Juan volcanic field (Colorado), Mount St. Helens (Cascade Range), Paintbrush and the Timber Mountains (southern Nevada), all of which plot in the ACM field. The volcanic suites associated with the extensional phase of volcanism during late Cenozoic include the Bandelier tuffs of the Jemez Volcanic Field, New Mexico, volcanic rocks from the Taos Plateau, the Latir Volcanic Field and Rio Grande. With the exception of the Latir rocks, these suites plot on the WPVZ field on Figures 2 and 4. The Latir rocks span both the ACM and the WPVZ fields. This overlap is not surprising, as the rocks are considered to be transitional, and include subduction-related andesites and early rift-related rhyolites (Lipman 1987). It appears that rift-generated felsic volcanic rocks retain the geochemical signature of their source rocks, at least in part.

SUMMARY

A revised version of the Ta/Yb – Th/Yb diagram and a new Th/Ta – Yb diagram define three major tectonic zones for felsic to intermediate volcanic rocks: Oceanic Arcs, Active Continental Margins (ACM) and Within-Plate Volcanic Zones (WPVZ). The three distinct zones are separated by diagonal, *ca.* 45%-trending lines on Figures 1 and 2, and by horizontal lines on Figures 3 and 4. Datasets within the individual zones have characteristic Th/Ta values; within-plate volcanic zones: *ca.*

1–6, active continental margins: >6–20, and oceanic arcs: >20–90.

The progressive enrichment in Th in the three sequential tectonic zones is attributed to the increasing contribution of an arc component, and the *ca.* 45° slope of the lines dividing the tectonic zones is attributed to the differences in degree of incompatibility among Ta, Th and Yb in felsic and intermediate volcanic rocks. The *ca.* 45° slope of the lines on Figures 1 and 2 differ from the dividing vertical line of Pearce at Ta/Yb = 0.1 (1983, Fig. 9), which separates oceanic arc basalts from continental margin basalts. It also differs from the almost horizontal lines on the same diagram that separate the fields of tholeiitic, calc-alkaline and shoshonitic arc basalts (Pearce 1983).

Our diagrams provide a much needed geochemical tool with which to discriminate among various tectonic environments of formation of felsic to intermediate volcanic rocks. As seen in Figures 1 and 2, the diagrams can be also used to interpret the tectonic evolution of a region and the geochemical evolution of the rocks (*i.e.*, transition from subduction to rift-related volcanism in the western United States, or the addition of a depleted MORB component to the source). Finally, as Ta, Th and Yb are considered to be immobile under most geological conditions and the Ta/Yb – Th/Yb values are expected to remain constant during metamorphism, the diagrams will be also useful in identifying the tectonic environment of rocks from ancient metamorphic terranes.

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APPENDIX 1. GEOCHEMICAL DATA FOR FELSIC AND INTERMEDIATE VOLCANIC ROCKS HOSTING THE SAN NICOLAS VMS DEPOSIT IN MEXICO

Sample #	SAL5871	SAL6037	SAL6056	SAL6454	SAL8734	SAL8751	SAL8637	SAL7895	SAL8720	SAL9039	SALB0114
La (ppm)	17.799	24.397	26.116	22.198	21.991	10.757	18.103	20.023	17.142	10.212	12.550
Ce	38.293	47.676	57.858	50.831	48.550	25.027	41.767	49.269	39.242	22.287	27.620
Nd	19.086	26.915	28.023	25.826	25.016	10.000	21.057	20.500	15.700	7.500	12.400
Sm	4.741	6.726	7.262	5.818	6.332	3.672	5.283	6.984	4.967	2.884	4.806
Eu	0.725	1.035	1.216	1.034	1.243	0.790	1.123	1.027	0.989	0.660	1.501
Tb	0.774	1.142	1.172	1.020	1.300	0.704	0.840	1.100	0.909	0.623	0.922
Yb	4.098	4.179	5.787	5.660	9.409	3.409	3.567	6.078	3.497	6.634	4.675
Lu	0.617	0.604	0.878	0.852	1.502	0.509	0.541	0.912	0.506	1.087	0.763
Ta	0.579	0.674	0.907	0.655	0.66	0.663	0.465	0.39	0.521	0.755	0.286
Th	7.374	7.084	8.537	7.08	7.017	6.713	4.13	3.496	5.045	5.386	2.04
Ta/Yb	0.14	0.16	0.16	0.12	0.07	0.19	0.13	0.06	0.15	0.11	0.06
Th/Yb	1.80	1.70	1.48	1.25	0.75	1.97	1.16	0.58	1.44	0.81	0.44
Th/Ta	12.74	10.51	9.41	10.81	10.63	10.13	8.88	8.96	9.68	7.13	7.13

Samples were analyzed for REE, Ta and Th by INA at the University of Toronto