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Application of four sets of tectonomagmatic discriminant function based diagrams to basic rocks from northwest Mexico

Aplicación de cuatro conjuntos de diagramas tectonomagmáticos basados en funciones discriminantes a rocas básicas del noroeste de México

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Abstract

Discrimination diagrams are being widely used for the past four decades to infer the tectonomagmatic affiliation of old rocks. There are several major- and trace-element composition based bivariate, ternary and multi-element discriminant function diagrams in the literature. Recent evaluation of the performance of these diagrams indicates that four sets of recent discriminant function based diagrams, in which the tectonic boundaries are determined from probability estimates for four tectonic settings of island arc, continental rift, ocean-island and mid-ocean ridge, have shown very high success rates. In this work, we have created an extensive geochemical database for on-land and off-shore basic rocks of northwest Mexico and applied these four sets of recent and highly successful tectonomagmatic discriminant function based diagrams to infer their tectonomagmatic origin. Each of these four sets of diagrams (two for major- and two for trace-elements) contained five diagrams. All the four sets of diagrams confirmed a continental rift setting for on-land basic rocks of <13 Ma age, with success rates of 71%-93% and 58%-90% for major-element and trace-element based diagrams, respectively. For the on-land basic rocks of >13 Ma age, major-element based diagrams also indicated a rift setting. However, one set of trace-element based discrimination diagrams indicated an arc to rift transition and the other set of trace- element based discrimination diagrams for the only sample from the Comondú arc, which has the required complete dataset, indicated an arc setting. All the four sets of discrimination diagrams indicated MORB setting (success rates 90%-98% and 100% for major-element and trace-element based diagrams, respectively) for off-shore rocks (most of the samples were obtained from DSDP drilled sites in the Gulf of California and some dredged rock samples from the Gulf of California) with very high success rates. All the inferred tectonic settings from these four sets of new discrimination diagrams, in general, are in conformity with those reported in the literature based on other methods. The results show that these discrimination diagrams may successfully discriminate the original tectonic setting of comparatively younger and older on-shore rocks as well as sea-water altered deep-sea rocks and dredged material.

Keywords: Basic rocks, geochemistry, tectonic setting, arc, rifting, discrimination diagrams

Resumen

Los diagramas de discriminación tectonomagmática han sido ampliamente utilizados en las últimas cuatro décadas para inferir la afiliación tectonomagmática de rocas antiguas. Hay numerosos diagramas discriminantes (bivariantes, ternarios, o de mayor dimensionalidad) en la literatura basados en la composición de los elementos mayores y traza. Las evaluaciones recientes del rendimiento de estos diagramas indican que los últimos cuatro conjuntos de diagramas tectonomagmáticos, en los que las fronteras tectónicas se determinan basándose en las estimaciones de probabilidades de cuatro configuraciones tectónicas (arco-isla, rift continental, islas oceánicas y dorsales oceánicas), han obtenido tasas de éxito muy alto. En este trabajo, hemos creado una amplia base de datos geoquímicos de rocas básicas obtenidas en tierra firme y en el Golfo de California, en el noroeste de México, y hemos aplicado estos diagramas recientes basados en las funciones discriminantes para deducir su contexto tectonomagmático original. Cada uno de estos cuatro conjuntos de diagramas (dos de elementos mayores y dos de elementos traza) contiene cinco diagramas. Cuando se introducen los datos de las rocas < 13 Ma de edad recogidas en tierra firme, todos los tipos de diagramas confirman la dominante configuración de rift continental con tasas de éxito de 71%-93% y 58%-90% para las diagramas de elementos mayores y traza, respectivamente. Para las rocas básicas de la tierra firme de > 13 Ma de edad, los diagramas de elementos mayores también indican una configuración tectónica dominante de rift continental. Sin embargo, un conjunto de diagramas de discriminación de elementos traza indica la transición de arco-isla a rift continental y otro conjunto de diagramas de elementos traza para una sola muestra del arco Comondú, indica configuración tectónica de arco-isla. Todos los tipos de diagramas de discriminación indican la configuración de MORB (tasas de éxito del 90%-98% y 100% para los elementos mayores y traza, respectivamente) para las rocas del Golfo de California (predominantemente de puntos perforados en el programa DSDP y de algunas muestras de rocas dragadas) con tasas de éxito muy altas. En general, todas las configuraciones tectónicas inferidas a partir de estos cuatro conjuntos de diagramas de discriminación están en conformidad con los reportados en la literatura usando otros métodos. Los resultados muestran que estos diagramas de discriminación pueden discriminar correctamente la configuración tectonomagmática original de rocas muestreadas en tierra firme, ya sean más jóvenes o más antiguas, así como de las rocas alteradas por el agua del mar y los materiales de dragado.

Palabras clave: Rocas básicas, geoquímica, ambiente tectónico, arco-isla, rift continental, diagramas de discriminación.

1. Introduction

Tectonomagmatic discrimination diagrams are being widely used to infer the original tectonic setting of volcanic rocks (e.g., Pearce *et al*., 1977; Rollinson, 1993; Verma, 2010). These diagrams are developed on two major basic assumptions: (1) concentrations of the characteristic chemical elements being used in the discriminate diagrams show large differences in the rocks of different tectonic settings; and (2) these characteristic chemical elements of the rocks are relatively immobile from the period of rock formation to the present.

There are several major- and trace-element composition based diagrams for geochemical tectonic discrimination in the literature, which may be grouped as follows: (1) bivariate diagrams (Pearce and Gale, 1977; Pearce and Norry, 1979; Shervais, 1982; Pearce, 1982; Vasconcelos-F. *et al*., 1998, 2001); (2) ternary diagrams (Pearce and Cann, 1973; Pearce *et al*., 1977; Wood, 1980; Mullen, 1983; Meschede, 1986; Cabanis and Lecolle, 1989); (3) discriminant function based diagrams (Butler and Woronow, 1986; Pearce, 1976; Agrawal *et al*., 2004); and (4) multi-element discriminant function diagrams based on log-transformed ratios (Verma *et al*., 2006; Agrawal *et al*., 2008; Verma and Agrawal, 2011). All these discrimination diagrams have been developed based on a geochemical database of the volcanic rocks from known tectonic environments. In majority of the above mentioned diagrams, the tectonic discrimination boundaries were drawn by eye, i.e., were based on visual appearance of the clustering of data points of known tectonic settings, except in a few recent ones (Agrawal *et al*., 2004; Verma *et al*., 2006; Agrawal *et al*., 2008; Verma and Agrawal, 2011), in which the tectonic boundaries are determined based on probability estimates. Agrawal (1999) and Agrawal and Verma (2007) had already criticized the subjective use of eye for drawing tectonic field boundaries.

Recently, there are extensive evaluations of existing diagrams, which indicated highly variable success rates in discriminating the tectonic settings (Vermeesch, 2006, 2007; Verma *et al*., 2006, 2010, 2011; Sheth, 2008; Verma, 2010). Verma (2012) has recently documented serious statistical problems with both bivariate and ternary diagrams; in fact, for ternary diagrams he used Monte Carlo simulations to show their inadequacy and proposed log-ratio transformation as the best alternative to replace conventional ternary diagrams. Sheth (2008) evaluated some of the diagrams (Verma *et al*., 2006; Vermeesch, 2006) with data of ocean-island, arc and mid-ocean ridge lavas from the Indian Ocean and reported that the log-ratio transformation and linear discriminant analysis appear to be powerful methods in tectonomagmatic discrimination studies. Verma (2010) evaluated a large number of bivariate, ternary and multi-dimensional diagrams and inferred that the newer diagrams proposed during 2004-2011 provide more reliable results. Similarly, Verma *et al.* (2011) have successfully applied these multi-element based dis-

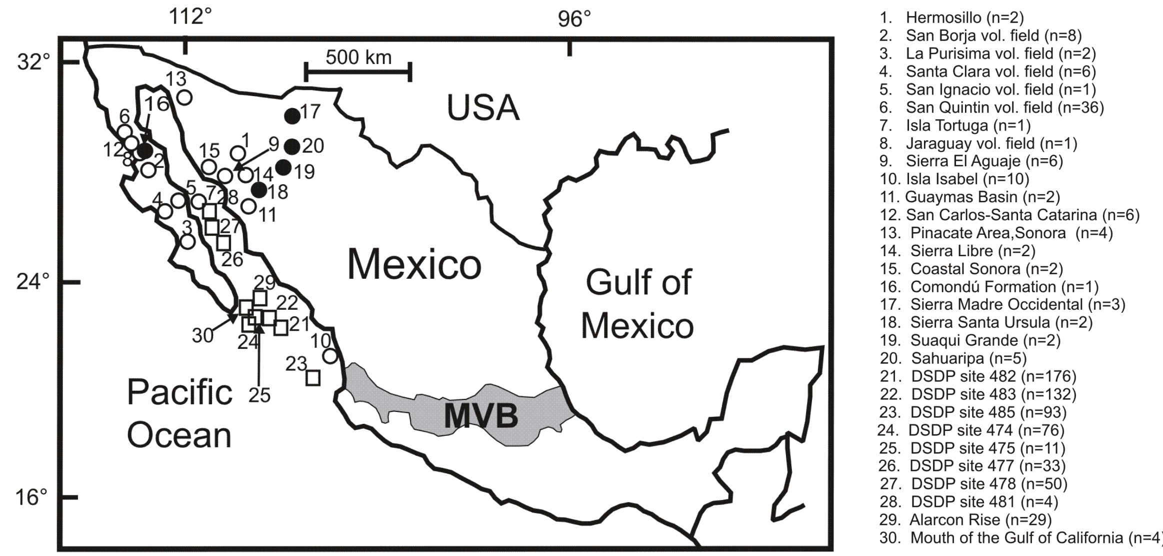

Fig. 1.- Schematic map showing the locations of the basic rock samples used in this study. The open and filled circles represent the on-shore basic rocks of <13 Ma and >13 Ma ages, respectively. The squares represent off-shore basic rocks. (MVB: Mexican Volcanic Belt).

Fig. 1.- Mapa esquemático mostrando la ubicación de las muestras de rocas básicas utiizadas en este estudio. Los círculos blancos y negros representan las rocas básicas muestreadas en tierra de <13 Ma y de >13 Ma años de edad, respectivamente. Los cuadrados representan las rocas básicas muestreadas en el mar. (MVB: Cinturón Volcánico Mexicano).

criminant diagrams for basic rocks of Southern Mexico and Central America for inferring their tectonomagmatic origin.

In this article, we have evaluated the more recent and highly successful multi-element discriminant function diagrams with simple elemental ratio variables (Agrawal *et al*., 2004) and based on log-transformed ratios (Verma *et al*., 2006; Agrawal *et al*., 2008; Verma and Agrawal, 2011) with an application to the basic rocks of on-land and off-shore of northwest Mexico.

2. Tectonic framework of the study area

The late Cenozoic tectonic framework of northwestern Mexico has been discussed in detail by several researchers (for example, Rogers *et al*., 1985; Saunders *et al*., 1987; Verma,2000; Luhr *et al*., 1995; Calmus *et al*., 2003) and hence, only a brief discussion is provided here. The west coast of northwestern Mexico has been a convergent plate boundary since mid-Cretaceous. The eastward subduction of oceanic lithosphere beneath western North America continued from the Cretaceous to about 29 Ma (Mammerickx and Klitgord, 1982). Towards the western part of northwestern Mexico, subduction related magmatism is represented by batholitic granitoids between 90 and 40 Ma (McDowell *et al*., 1997, 2001), whereas towards the east of the Baja California peninsula, a continuous subduction related magmatism during Eocene-Oligocene (between 38 and 23 Ma) has generated important inland magmatism along the Sierra Madre Occidental belt (McDowell and Keizer, 1977; Stock and Lee, 1994; Benoit *et al*., 2002). Afterwards, during the Lower Miocene, the volcanic front shifted towards the west, forming the magmatic arc (the Comondú arc) all along the Baja California Peninsula. This volcanic belt had a longer activity between 24 and 12 Ma in southern Baja California compared to northern Baja California where Miocene (21 to 16 Ma) volcanism constituted several volcanic fields. The subduction in this region ended at about 12.9 Ma (Mammerickx and Klitgord, 1982; Calmus *et al*., 2003). Afterwards, a transform boundary was developed between Pacific and North America plates parallel to the Pacific margin of Baja California (Spencer and Normark, 1979). Consequently, the tectonic setting has changed from subduction to rifting along the western margin of North America in Late-Cenozoic time (Grijalva-Noriega and Roldán-Quintana, 1998).

3. Methodology

We have prepared a database by compiling geochemical data of basic rocks of northwest Mexico from the published articles. For this purpose, we considered the basic rocks of on-land (Baja California, Baja California Sur and Sonora states of Mexico) and the off-shore (mainly from the DSDP sites of Gulf of California and a few from Alarcon Rise, and dredged rocks from three sites near the mouth of the Gulf of California and close to the

East Pacific Rise) regions of northwest Mexico (Fig. 1). The geochemical data from the above mentioned regions were obtained from the published articles that were not included in any of the previous studies, in which the diagrams to be applied were proposed, i.e., not included in the databases used by Agrawal *et al*. (2004, 2008), Verma *et al*. (2006), and Verma and Agrawal (2011).

The literature sources for on-land geochemical data were as follows: Saunders *et al*. (1987); Luhr *et al*. (1995); Aguillón-Robles *et al*. (2001); Benoit *et al*. (2002); Calmus *et al*. (2003); Solano *et al*. (2005); Bellon *et al*. (2006); Pallares *et al*. (2007); Vidal-Solano *et al*. (2008); Till *et al*. (2009) ; Housh *et al*. (2010) ; and Calmus *et al*. (2011). The literature sources for the off-shore geochemical data were as follows: Lopez *et al*. (1978); Jochum and Verma (1996); Castillo *et al*. (2002); Flower *et al*. (2007); Morrison and Thompson (2007); Perfit *et al*. (2007); Saunders (2007); Saunders *et al*. (2007); and Zolotarev and Margolin (2007).

Based on the geochemical data, rock types were determined using SINCLAS computer program (Verma *et al*. 2002, 2003), with the Middlemost (1989) option for Fe-oxidation adjustment. This program requires the complete chemical analyses, involving all ten major elements (with total Fe as Fe_2O_3 or FeO), for the rock samples. Only basic rock types having $(SiO_2)_{adj}$ < 52% (Le Bas *et al*., 1986) as inferred from the SINCLAS software were considered for this study. With this condition, we have left with the chemical data for only 102 basic rocks from the on-shore region. The number of samples (n) from the specific areas (Fig. 1) were as follows: Hermosillo (n=2), San Borja volcanic field (n=8), La Purísima volcanic field (n=2), Santa Clara volcanic field (n=6), San Ignacio volcanic field (n=1), San Quintín volcanic field (n=36), Isla Tortuga (n=1), Jaraguay volcanic field (n=1), Sierra El Aguaje (n=6), Isla Isabel (n=10), Guaymas Basin (n=2), San Carlos-Santa Catarina (n=6), Pinacate Area, Sonora (n=4), Sierra Libre (n=2), Coastal Sonora (n=2), Comondú Formation (n=1), Sierra Madre Occidental (n=3), Sierra Santa Ursula (n=2), Suaqui Grande (n=2), and Sahuaripa (n=5). Similarly, we have chemical data for 612 basic rocks from the offshore region (Fig. 1). These offshore chemical data are from the rocks of DSDP site 482 (n=176), DSDP site 483 (n=132), DSDP site 485 (n=93), DSDP site 474 (n=76), DSDP site 475 (n=11), DSDP site 477 (n=33), DSDP site 478 (n=50), DSDP site 481 (n=4), Alarcon Rise lava from Gulf of California (n=29), Mouth of the Gulf of California (n=4; dredged rocks from the mouth of the Gulf of California; including 8 subdivided parts of three of these dredged rocks), and

Locality	Discrimination function discrimination diagram	Total number of samples	Number of discriminated samples (%)			
			IAB (1)	CRB (2)	OIB (3)	MORB (4)
On-land basic rocks (<13 Ma)	1-2-3-4	89	0 (0)	***63 (71)***	4 (4)	22 (25)
	1-2-3	89	13 (15)	***75 (84)***	1 (1)	---
	1-2-4	89	2 (2)	***67 (75)***	---	20 (23)
	1-3-4	89	3 (3)	---	50 (56)	36 (41)
	2-3-4	89	---	***76 (86)***	3 (3)	10 (11)
On-land basic rocks (>13 Ma)	1-2-3-4	13	3 (23)	***10 (77)***	0	0
	1-2-3	13	4 (31)	***9 (69)***	0	---
	1-2-4	13	5 (38)	***8 (62)***	---	0
	1-3-4	13	5 (38.5)	---	5 (38.5)	3 (23)
	2-3-4	13	---	***12 (92)***	0	1 (8)
Off-shore rocks	1-2-3-4	608	4 (1)	9 (1)	46 (8)	***549 (90)***
	1-2-3	608	227 (37)	98 (16)	283 (47)	---
	1-2-4	608	2 (0.3)	17 (2.8)	---	***589 (96.9)***
	1-3-4	608	5 (1)	---	38 (6)	***565 (93)***
	2-3-4	608	---	6 (1)	51 (8)	***551 (91)***
Sea-floor dredged material	1-2-3-4	3	0	0	0	***3***
	1-2-3	3	***3***	0	0	---
	1-2-4	3	0	0	---	***3***
	1-3-4	3	0	---	0	***3***
	2-3-4	3	---	0	0	***3***

Table 1.- Information on tectonomagmatic origin obtained from the set of five discriminant function based discrimination diagrams of Agrawal *et al*. (2004) for on-land and off-shore basic rocks of northwest Mexico. Boldface italic font indicates the inferred tectonic setting (IAB: island arc, CRB: continental rift, OIB: ocean-island, MORB: mid-ocean ridge).

Tabla 1.- Información sobre el origen tectonomagmático obtenido a partir del conjunto de los cinco diagramas de discriminación basados en la función discriminante de Agrawal *et al*. (2004) para las rocas básicas del noroeste de México estudiadas en este trabajo. La fuente negrita y cursiva indica el ambiente tectónico inferido (IAB: arco-isla, CRB: rift continental, OIB: isla oceánica, MORB: dorsal oceánica).

Locality	Discrimination function discrimination diagram	Total number of samples	Number of discriminated samples (%)			
			IAB (1)	CRB (2)	OIB (3)	MORB (4)
On-land basic rocks (<13 Ma)	1-2-3-4	89	1 (1)	***71 (80)***	11 (12)	6 (7)
	1-2-3	89	1 (1)	***83 (93)***	5 (6)	---
	1-2-4	89	1 (1)	***81 (91)***	---	7 (8)
	1-3-4	89	9 (10)	---	52 (58)	28 (32)
	2-3-4	89	---	***80 (90)***	2 (2)	7 (8)
On-land basic rocks (>13 Ma)	1-2-3-4	13	3 (23)	***10 (77)***	0	0
	1-2-3	13	2 (15)	***11 (85)***	0	---
	1-2-4	13	2 (15)	***11 (85)***	---	0
	1-3-4	13	7 (54)	---	3 (23)	3 (23)
	2-3-4	13	---	***12 (92)***	0	1 (8)
Off-shore rocks	1-2-3-4	608	4 (0.7)	2 (0.3)	15 (2.5)	***587 (96.5)***
	1-2-3	608	5 (1)	37 (6)	566 (93)	---
	1-2-4	608	5 (1)	4 (1)	---	***599 (98)***
	1-3-4	608	4 (1)	---	61 (10)	***543 (89)***
	2-3-4	608	---	4 (1)	20 (3)	***584 (96)***
Sea-floor dredged material	1-2-3-4	3	0	0	0	***3***
	1-2-3	3	1	1	1	---
	1-2-4	3	1	0	---	***2***
	1-3-4	3	0	---	0	***3***
	2-3-4	3	---	0	0	***3***

Table 2.- Information on tectonomagmatic origin obtained from the set of five discriminant function based discrimination diagrams of Verma *et al*. (2006) for on-land and off-shore basic rocks of northwest Mexico. Boldface italic font indicates the inferred tectonic setting (IAB: island arc, CRB: continental rift, OIB: ocean-island, MORB: mid-ocean ridge).

Tabla 2.- Información sobre el origen tectonomagmático obtenido a partir del conjunto de los cinco diagramas de discriminación basados en la función discriminante de Verma *et al*. (2006) para las rocas básicas del noroeste de México estudiadas en este trabajo. La fuente negrita y cursiva indica el ambiente tectónico inferido (IAB: arco-isla, CRB: rift continental, OIB: isla oceánica, MORB: dorsal oceánica).

other deep-sea samples (seamount, basin stations, etc; n=4). Natural log-transformed ratios for major elements were calculated as follows: $\ln(TiO_2/SiO_2)_{adj}$, $\ln(Al_2O_3/SiO_2)_{adj}$, $\ln(Fe_2O_3/SiO_2)_{adj}$, $\ln(FeO/SiO_2)_{adj}$, $\ln(MnO/SiO_2)_{adj}$, $\ln(MgO/SiO_2)_{adj}$, $\ln(CaO/SiO_2)_{adj}$, $\ln(Na_2O/SiO_2)_{adj}$, $\ln(K_2O/SiO_2)_{adj}$, and $\ln(P_2O_5/SiO_2)_{adj}$, in which $(SiO_2)_{adj}$ was used as the common denominator.

In general, ~13 Ma BP is considered as the end of subduction along the northwestern Mexico (Mammerickx and Klitgord, 1982; Calmus *et al*., 2003). We have grouped our on-land basic rock samples in rocks of >13 Ma ages (as subduction-arc magmatism) and <13 Ma (as rift magmatism) to identify their diverse tectonic settings. The diagrams of Agrawal *et al*. (2004) and Verma *et al*. (2006) are based on major-elements (the first with simple ratio variables and the second with log-transformation of ratio variables), whereas those of Agrawal *et al*. (2008) and Verma and Agrawal (2011) use log-transformed ratios of immobile-elements (La, Sm, Yb, Nb, and Zr for the former and adjusted TiO_2, Nb, V, Y, and Zr for the latter). In all the above-mentioned four sets of new discriminant function based tectonomagmatic diagrams, there is no differentiation between the continental and oceanic arc settings, and the entire arc setting is represented by island arc setting (IAB). Based on the availability of the required chemical data in the above mentioned literature for the application of these four sets of recent tectonomagmatic discriminant function based diagrams for basic rocks, we obtained the final number of samples for each diagram as follows: (1) 89, 13, and 611 rock samples for on-land basic rocks of younger age (<13 Ma), on-land basic rocks of older age (>13 Ma) and off-shore rocks (including 3 sea-floor dredged rocks), respectively, for the major-element concentrations based discrimination diagrams of Agrawal *et al*. (2004) and Verma *et al*. (2006); (2) 80, 13, and 8 rock samples for on-land basic rocks of younger age (<13 Ma), on-land basic rocks of older age (>13 Ma) and sea-floor dredged rocks (different parts of three rock samples), respectively, for the immobile trace-elemental concentrations based discrimination diagram of Agrawal *et al*. (2008); and finally, (3) 68, 1, and 78 rock samples for on-land basic rocks of younger age (<13 Ma), on-land basic rocks of older age (>13 Ma) and off-shore rocks, respectively, for the immobile trace-element concentrations based discrimination diagram of Verma and Agrawal (2011). In the literature, chemical data for basic rocks are limited in comparison to acidic rocks. Chemical data for the older (>13 Ma age) basic rocks are further lacking as compared to the basic rocks of <13 Ma age. Among the compiled chemical data for

Locality	Discrimination function discrimination diagram	Total number of samples	Number of discriminated samples (%)				
			IAB (1)	CRB (2)	CRB (2) + OIB (3)	OIB (3)	MORB (4)
On-land basic rocks (<13 Ma)	1-2+3-4	80	12 (15)	---	***64 (80)***	---	4 (5)
	1-2-3	80	14 (17)	***46 (58)***	---	20 (25)	---
	1-2-4	80	12 (15)	***64 (80)***	---	---	4 (5)
	1-3-4	80	11 (14)	---	---	61 (76)	8 (10)
	2-3-4	80	---	***52 (65)***	---	21 (26)	7 (9)
On-land basic rocks (>13 Ma)	1-2+3-4	13	4 (31)	---	***9 (69)***	---	0
	1-2-3	13	***5 (38.5)***	***5 (38.5)***	---	3 (23)	---
	1-2-4	13	4 (31)	***9 (69)***	---	---	0
	1-3-4	13	4 (31)	---	---	8 (61)	1 (8)
	2-3-4	13	---	***10 (77)***	---	2 (15)	1 (8)
Altered glass	1-2-3-4	2	***1***	---	0	---	***1***
	1-2-3	2	***1***	0	---	***1***	---
	1-2-4	2	***1***	0	---	---	***1***
	1-3-4	2	***1***	---	---	0	***1***
	2-3-4	2	---	0	---	0	***2***
Margin	1-2+3-4	3	1	---	0	---	***2***
	1-2-3	3	1	0	---	***2***	---
	1-2-4	3	1	0	---	---	***2***
	1-3-4	3	1	---	---	0	***2***
	2-3-4	3	---	0	---	0	***3***
Core samples	1-2+3-4	3	0	---	0	0	***3***
	1-2-3	3	0	0	---	***3***	---
	1-2-4	3	0	0	---	---	***3***
	1-3-4	3	0	---	---	0	***3***
	2-3-4	3	---	0	---	0	***3***

Table 3. Information on tectonomagmatic origin obtained from the set of five discriminant function based discrimination diagrams of Agrawal *et al*. (2008) for on-land and off-shore basic rocks of northwest Mexico. Boldface italic font indicates the inferred tectonic setting (IAB: island arc, CRB: continental rift, OIB: ocean-island, MORB: mid-ocean ridge).

Tabla 3. Información sobre el origen tectonomagmático obtenido a partir del conjunto de los cinco diagramas de discriminación basados en la función discriminante de Agrawal *et al*. (2008) para las rocas básicas del noroeste de México estudiadas en este trabajo. La fuente negrita y cursiva indica el ambiente tectónico inferido (IAB: arco-isla, CRB: rift continental, OIB: isla oceánica, MORB: dorsal oceánica).

on-land basic rocks, only one rock sample of >13 Ma age contained the necessary immobile trace element data to plot in the diagram of Verma and Agrawal (2011) which shows the dearth of trace element chemical data for the rocks of this region.

4. Results and Discussion

The compiled geochemical data of on-land and off-shore basic rocks of northwest Mexico are plotted in all four sets of new discrimination diagrams (Agrawal *et al*., 2004, 2008; Verma *et al*., 2006; Verma and Agrawal, 2011) to infer the tectonomagmatic origin of these rocks. For each set of diagrams, five different plots were prepared, which provided a total of 20 diagrams. The samples in different tectonic setting fields were counted and their percentage range in each tectonic setting was calculated (wherever number of samples >13) and reported (Figs. 2-5; Tables 1-4). We discuss below only the dominant or most probable tectonic settings inferred by these diagrams for each group of rocks. All the indicated dominant tectonic setting are statistically significant because they are >>33.3% (being the simple "by chance" probability). The results are summarized in Tables 1-4. These results were fully consistent with those resulting from the application of computer program TecD (Verma and Rivera-Gómez, 2012).

4.1. Tectonomagmatic origin of on-shore basic rocks of northwest Mexico

Two sets of major-element (Agrawal *et al*., 2004, Fig. 2, Table 1; Verma *et al*., 2006, Fig. 3, Table 2) and two sets of immobile trace-element (Agrawal *et al*., 2008; Fig. 4; Table 3; Verma and Agrawal, 2011; Fig. 5; Table 4) based discrimination diagrams were applied for discrimination of island arc (IAB), continental rift (CRB), ocean-island (OIB) and mid-ocean ridge (MORB) tectonic settings. Out of the five diagrams in each of the two sets of major-element based diagrams, the first diagram

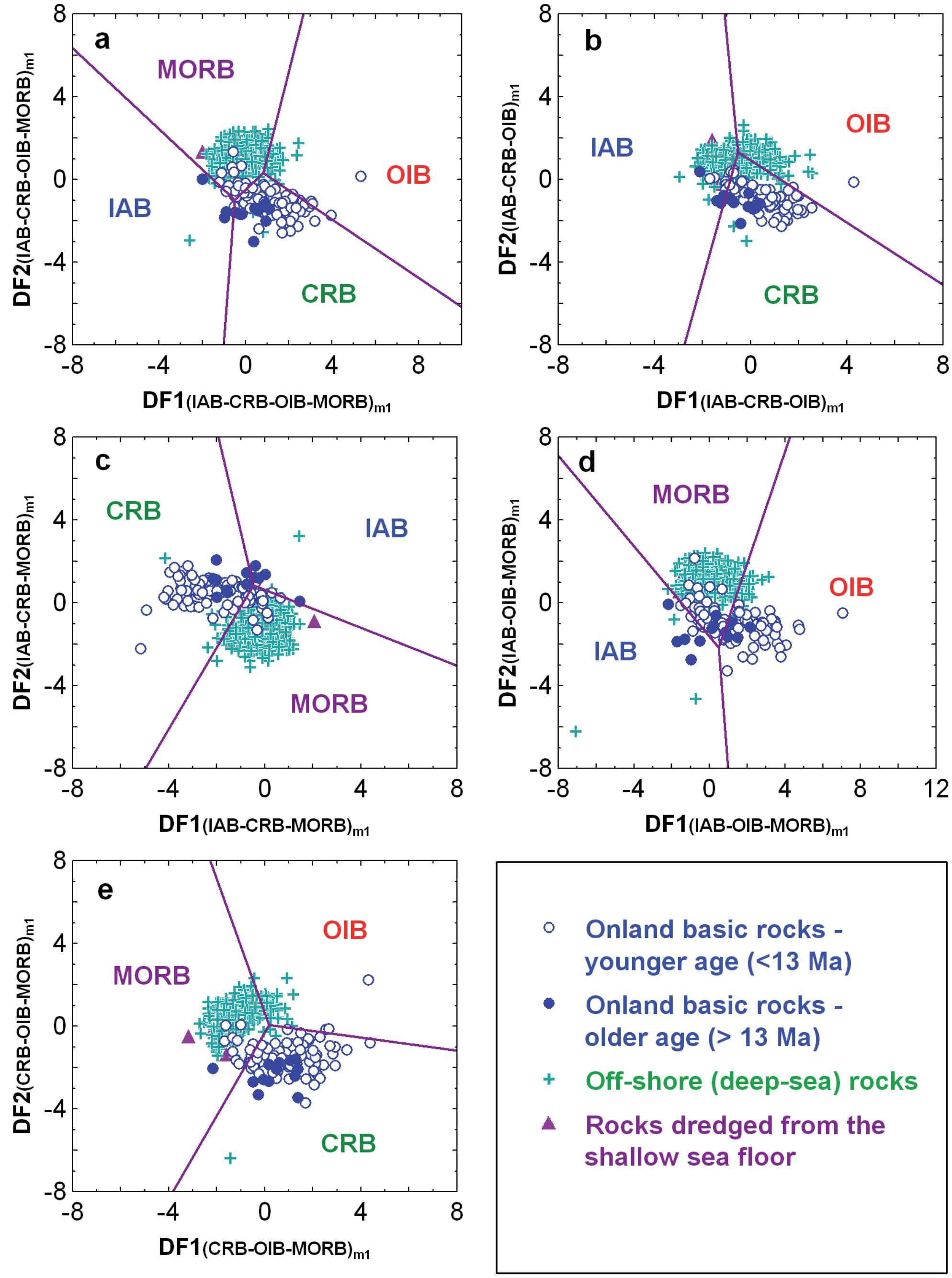

Fig. 2.-Application of the major-element discriminant function based discrimination diagrams of Agrawal *et al*. (2004) for basic rocks from northwestern Mexico. (IAB: island arc, CRB: continental rift, OIB: ocean-island, MORB: mid-ocean ridge).

Fig. 2.-Aplicación de los diagramas discriminantes basados en elementos mayores y en la función de discriminación de Agrawal *et al*. (2004) para rocas básicas del noroeste de México. (IAB: arco-isla, CRB: rift continental, OIB: isla oceánica, MORB: dorsal oceánica).

contains four tectonic settings and other four diagrams with three settings at a time.

The first set of major-element based discrimination diagrams of Agrawal *et al*. (2004; Fig. 2; Table 1) indicated the tectonic setting of continental rift (success rates of 71%-86%) for on-land basic rocks of <13 Ma age (a total of 89 samples were available). For on-land basic rocks of >13 Ma age, these diagrams also indicated the tectonic setting of continental rift although the total number of samples was much less (only 13, of which 8 to 12 plotted in CRB). In diagrams with both CRB and IAB settings (Fig. 2a-c), the samples were divided in these two tectonic settings, i.e., 8 to 10 samples plotted in CRB and the remaining 5 to 3 in IAB (Table 1).

When we used exactly the same samples as for the first set, the second set of major-element based diagrams of Verma *et al*. (2006; Fig.3; Table 2) also revealed the dominant continental rift setting with still higher success rates (80%-93%) for on-land basic rocks of <13 Ma age than the Agrawal *et al.* (2004) diagrams. For on-land basic rocks of >13 Ma age, similar to the first set of diagrams, these second set of major-element based diagrams indicated the tectonic setting of continental rift (10 to 12 samples out of 13 plotted in the rift field; Fig. 3; Table 2).

The first set of immobile trace element based diagrams of Agrawal *et al*. (2008; Fig. 4; Table 3) was also applied for IAB, CRB, OIB, and MORB (all five diagrams

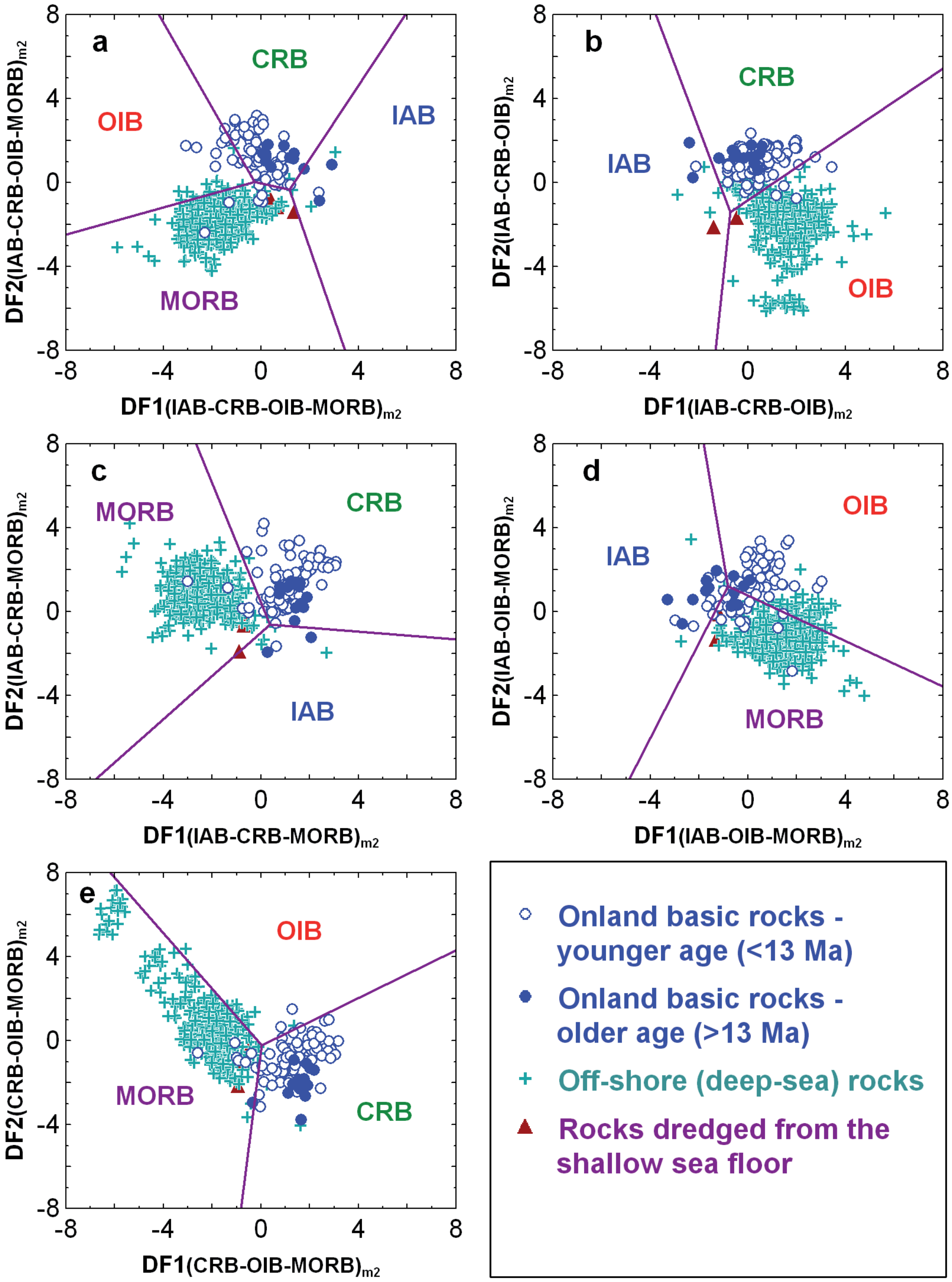

Fig. 3.-Application of the major-element discriminant function based discrimination diagrams of Verma *et al*. (2006) for basic rocks from northwestern Mexico. (IAB: island arc, CRB: continental rift, OIB: ocean-island, MORB: mid-ocean ridge).

Fig. 3.-Aplicación de los diagramas discriminantes basados en elementos mayores y en la función de discriminación de Verma *et al*. (2006) para rocas básicas del noroeste de México. (IAB: arco-isla, CRB: rift continental, OIB: isla oceánica, MORB: dorsal oceánica).

contains three tectonic settings at a time). The indicated tectonic settings are: (1) the dominant continental rift setting (success rates of 58%-80%) for 80 samples of on-land basic rocks of <13 Ma age; (2) when there is no individual CRB setting in the diagrams (Figs. 4a and 4d), the on-land basic rocks of <13 Ma age have plotted, respectively, in the combined tectonic field settings of CRB+OIB (with a high success rate of 80%) and OIB (with a high success rate of 76%); and (3) continental rift tectonic setting (5 to 10 samples out of 13 plotted in this field; Fig. 4; Table 3) for on-land basic rocks of >13 Ma age, with 4 to 5 samples (out of 13) plotting in the arc field.

Finally, the second set of immobile-element based diagrams of Verma and Agrawal (2011; Fig. 5; Table 4) was also applied for IAB, CRB, OIB, and MORB (three settings at a time in all the five diagrams). These immobile-element based diagrams of Verma and Agrawal (2011; Fig. 5; Table 4) complies the requirement of normal distribution of the log-ratio variables. This was achieved by identification and elimination of outlier data points by using the software DODESSYS (Verma and Díaz-González, 2012), which allows the application of the multiple-test method initially proposed by Verma (1997) and uses new precise and accurate critical values for discordancy tests (Barnett and Lewis, 1994; Verma and Qui-

Locality	Discrimination function discrimination diagram	Total number of samples	Number of discriminated samples (%)				
			IAB (1)	CRB (2)	CRB (2) + OIB (3)	OIB (3)	MORB (4)
On-land basic rocks (<13 Ma)	1-2+3-4	68	3 (4)	---	***60 (89)***	---	5 (7)
	1-2-3	68	6 (9)	***45 (66)***	---	17 (25)	---
	1-2-4	68	3 (4)	***61 (90)***	---	---	4 (6)
	1-3-4	68	3 (4)	---	---	52 (77)	13 (19)
	2-3-4	68	---	***45 (66)***	---	18 (27)	5 (7)
On-land basic rocks (>13 Ma)	1-2+3-4	1	***1***	---	0	---	0
	1-2-3	1	***1***	0	---	0	---
	1-2-4	1	***1***	0	---	---	0
	1-3-4	1	***1***	---	---	0	0
	2-3-4	1	---	0	---	0	1
Off-shore rocks	1-2-3-4	78	0 (0)	---	0 (0)	---	***78 (100)***
	1-2-3	78	75 (96)	3 (4)	---	0 (0)	---
	1-2-4	78	0 (0)	0 (0)	---	---	***78 (100)***
	1-3-4	78	0 (0)	---	---	0 (0)	***78 (100)***
	2-3-4	78	---	0 (0)	---	0 (0)	***78 (100)***

Table 4. Information on tectonomagmatic origin obtained from the set of five discriminant function based discrimination diagrams of Verma and Agrawal (2011) for on-land and off-shore basic rocks of northwest Mexico. Boldface italic font indicates the inferred tectonic setting (IAB: island arc, CRB: continental rift, OIB: ocean-island, MORB: mid-ocean ridge).

Tabla 4. Información sobre el origen tectonomagmático obtenido a partir del conjunto de los cinco diagramas de discriminación basados en la función discriminante de Verma y Agrawal (2011) para las rocas básicas del noroeste de México estudiadas en este trabajo. La fuente negrita y cursiva indica el ambiente tectónico inferido (IAB: arco-isla, CRB: rift continental, OIB: isla oceánica, MORB: dorsal oceánica).

roz-Ruiz, 2006a, 2006b, 2008; Verma *et al*., 2008). The indicated tectonic settings are as follows: continental rift setting (66%-90%) for on-land basic rocks of <13 Ma age and island-arc setting for the only one on-land basic rock sample of >13 Ma age.

The observed tectonomagmatic settings by the new discriminant function based tectonomagmatic settings for younger (<13 Ma age) on-land basic rocks are fully in concordance with those reported in the literature. The two sets of major-element (success rates of 71%-86%, Agrawal *et al*., 2004; success rates of 80%-93%, Verma *et al*., 2006) and two sets of trace-element (success rates of 58%-80%, Agrawal *et al*., 2008; success rates of 66%-90%, Verma and Agrawal, 2011) based discrimination diagrams confirm the dominant continental rift setting (CRB; Tables 1-4; Figs. 2-5) for on-land basic rocks of <13 Ma age. This is in agreement with that of the literature. The subduction of oceanic (Pacific) lithosphere beneath western North America continued from Cretaceous and ended at 12.9 Ma (Mammerickx and Klitgord, 1982; Calmus *et al*., 2003). After this period, during Late-Cenozoic, a transform boundary is developed between Pacific and North America plates parallel to the Pacific margin of Baja California (Spencer and Normark, 1979) which resulted in change of the tectonic setting from subduction to rifting along the western margin of North America (Grijalva-Noriega and Roldán-Quintana, 1998).

For the on-land basic rocks of >13 Ma age, we may draw the following inferences: (1) the major-element based diagrams of Agrawal *et al*. (2004; Table 1; Fig. 2) and Verma *et al*. (2006; Table 2; Fig. 3) indicated continental rift setting for the limited number of samples (only 13) with high success rates (62%-92% and 77%-92%, respectively), with most of the remaining samples plotting in the island arc setting; and (2) the trace-element based discrimination diagrams of Agrawal *et al*. (2008; Table 3; Fig. 4) and Verma and Agrawal (2011; Table 4; Fig. 5) provided less clear results, because, in the Agrawal *et al.* (2008) set, the samples indicated a continental rift setting with much lower success rates (38%-77%) and in the Verma and Agrawal (2011) set, the only sample (from the Comondú arc) plotted in the island arc field. In both of these two sets of the trace-element based diagrams (Agrawal *et al*., 2008; Verma and Agrawal, 2011) only two out of five diagrams in each set have both IAB and CRB fields (Table 3 and 4; Fig. 4 and 5). In these two diagrams of Agrawal *et al*. (2008), one diagram (Fig. 4b) indicated a combined CRB-IAB setting (equal number of samples plotted in both CRB and IAB; Table 3) and the other diagram (Fig. 4c) indicated a dominant CRB setting (9 out of 13 samples plotted in CRB and the remaining 4 samples in the IAB field). We may, therefore, conclude that these diagrams (Agrawal *et al*., 2008) may be interpreted as indicating a transition from an arc to rift setting.

The only rock sample with complete dataset for the Verma and Agrawal (2011) diagrams is plotted in the IAB field (Table 4 and Fig. 5a-d); whereas in the fifth diagram (Fig. 5e), where IAB field is not there, this sample is plot-

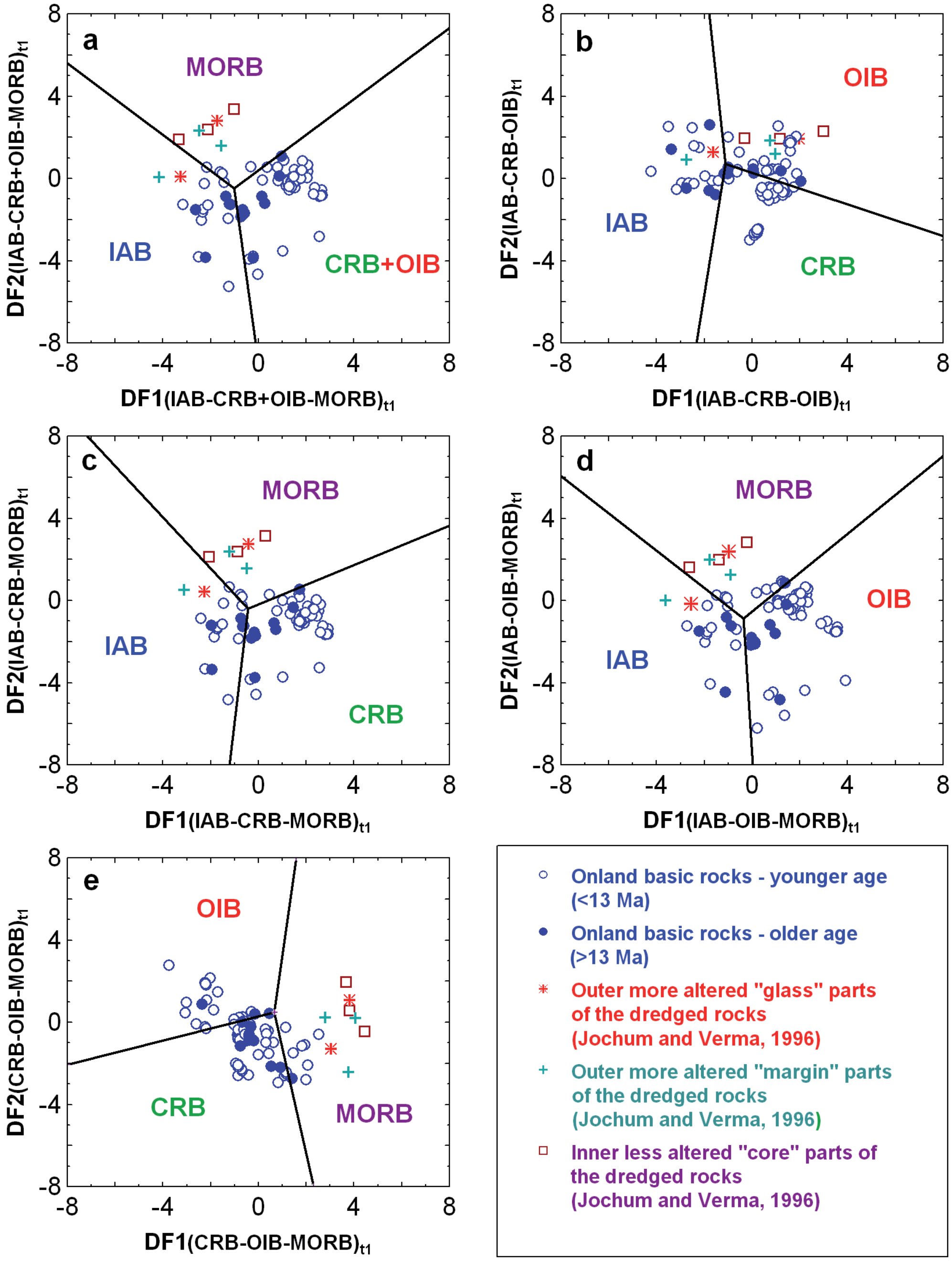

Fig. 4.-Application of the trace-element discriminant function based discrimination diagrams of Agrawal *et al.* (2008) for basic rocks from northwestern Mexico. (IAB: island arc, CRB: continental rift, OIB: ocean-island, MORB: mid-ocean ridge).

Fig. 4.-Aplicación de los diagramas discriminantes basados en elementos traza y en la función de discriminación de Agrawal *et al.* (2008) para rocas básicas del noroeste de México. (IAB: arco-isla, CRB: rift continental, OIB: isla oceánica, MORB: dorsal oceánica).

ted in the MORB field.

Among the 13 older on-land basic rocks (>13 Ma), nine rocks belongs to Southern Sonora (19-28 Ma; Till *et al.*, 2009), three rocks (27-45 Ma age; Albrecht and Goldstein, 2000) belong to Sierra Madre Occidental, northwestern Mexico and the one rock (20.06 Ma age; Pallares *et al.*, 2007) belongs to Comondú Formation (from Cataviña; Pallares *et al.*, 2007). It is reported that the Sierra Madre Occidental and Comondú arc were formed as the result of the subduction of oceanic lithosphere beneath western North America during Eocene-Oligocene and Lower Miocene respectively (McDowell and Keizer, 1977; Stock and Lee, 1994; Benoit *et al.*, 2002). Recently, Till *et al.* (2009) have reported that mafic volcanic rocks erupted in southern Sonora from 27 to 8 Ma have continental arc signature and appear to be derived from the metasomatized sub-arc mantle below Sonora. They were also of the opinion that the geochemistry of the rocks of Sonora is not consistent with the predictions of petrotectonic models and contrasts with central and southern Baja. The chemical data reported for basic rocks in the article of Till *et al.* (2009) were already included in the database of this work. As discussed above, all the four recent tectonic discriminate diagrams for basic rocks (Agrawal *et al.*, 2004; Verma *et al.*, 2006; Agrawal *et al.*, 2008; Verma and Agrawal, 2011) have indicated the continental rift

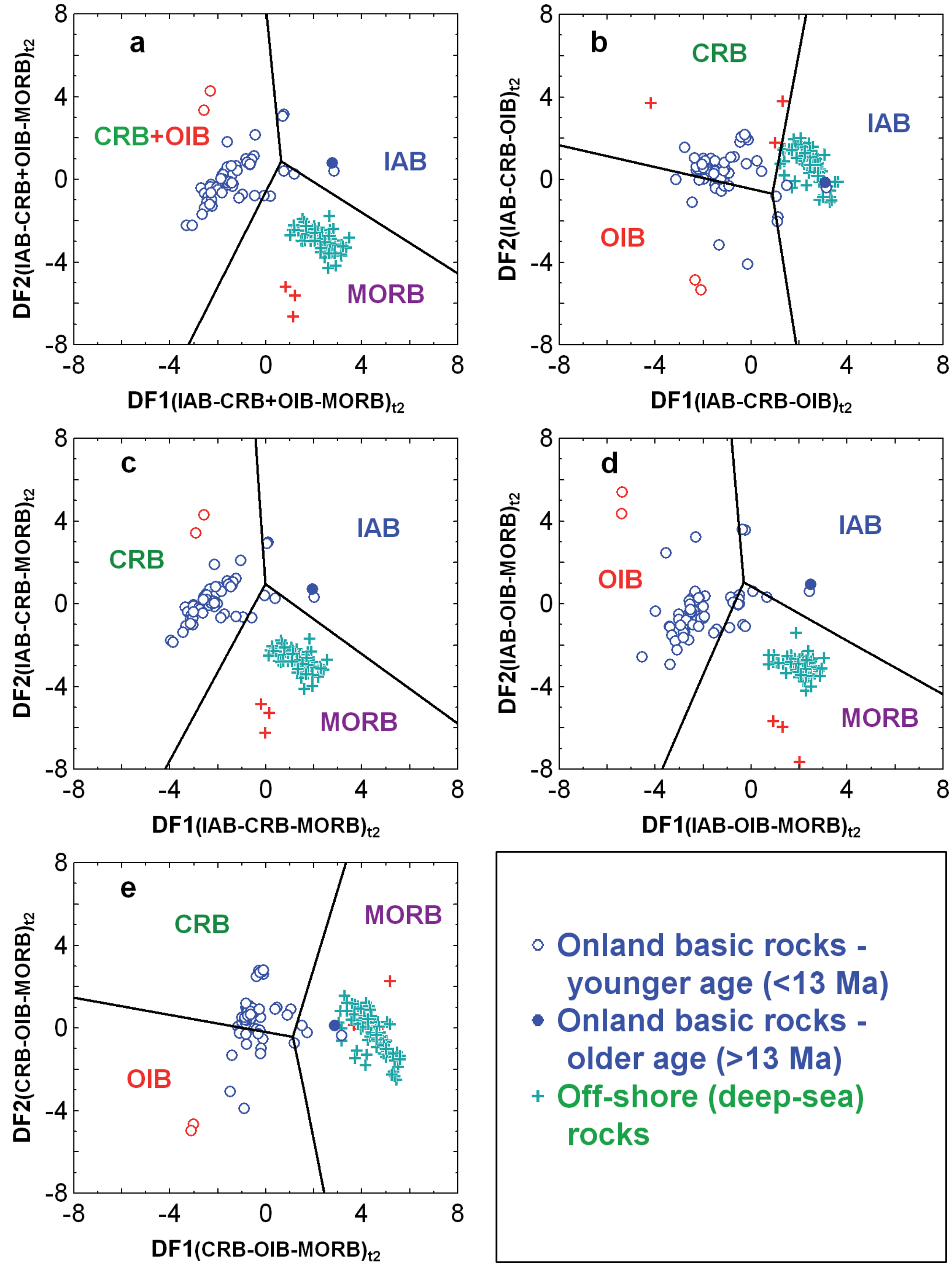

Fig. 5.- Application of the trace-element discriminant function based discrimination diagrams of Verma and Agrawal (2011) for basic rocks from northwestern Mexico. The samples marked with red color are outliers. (IAB: island arc, CRB: continental rift, OIB: ocean-island, MORB: mid-ocean ridge).

Fig. 5.- Aplicación de los diagramas discriminantes basados en elementos traza y en la función de discriminación de Verma y Agrawal (2011) para rocas básicas del noroeste de México. Las muestras marcadas en color rojo son los valores desviados. (IAB: arco-isla, CRB: rift continental, OIB: isla oceánica, MORB: dorsal oceánica).

setting (CRB) for rocks of <13 Ma. For older rocks (>13 Ma) also, three sets of diagrams (Agrawal *et al.*, 2004; Verma *et al.*, 2006; Agrawal *et al.*, 2008) indicated a rift setting, with the exception of Verma and Agrawal (2011) diagrams which indicated an arc setting for the unique sample from the Comundú arc.

For further clarity, we have applied the new discriminant-function-based multi-dimensional diagrams for acid (Verma *et al.*, 2012) and intermediate rocks (Verma and Verma, 2013) reported in Till *et al.* (2009). The tectonic discriminant diagrams for both acid and intermediate rocks have indicated a dominant rift setting. This is consistent with the inferred dominant rift setting by the four sets of discriminate diagrams for basic rocks <13 Ma and three sets of diagrams for basic rocks >13 Ma age, discussed above, although Till *et al.* (2009) envisioned an arc setting for mafic volcanic rocks (27 to 8 Ma age) from Sonora. Our results thus do not support the contention of Till *et al.* (2009) regarding the tectonic setting of their data.

Because the older samples (>13 Ma) come from widely different localities (12 from locations 17-20 in mainland Mexico and one from location 16 in Baja California; Fig. 1) and the rock samples from locations 17-20 might be away from the possible arc environment, they have not indicated a concrete arc setting. However, it is interesting to note that in all four sets of diagrams (Figs. 2-5), the only sample from the Comundú arc consistently plots in the arc field. This emphasizes the need of more data from the Comundú arc to understand the functioning of these diagrams.

4.2. Tectonomagmatic origin of off-shore basic rocks of northwest Mexico

The first set of major-element based discrimination diagrams of Agrawal *et al*. (2004; Fig. 2; Table 1) have indicated the tectonic setting of MORB (success rates of 90%-97%) for the off-shore rocks off northwest Mexico. When there is no MORB setting in the diagram (Fig. 2b), the samples occupied OIB (47%) and IAB (37%) settings.

When we used exactly the same samples as for the first set, the second set of major-element based diagrams of Verma *et al*. (2006; Fig.3; Table 2) also indicated the MORB setting (88%-98%). When in a diagram there is no tectonic setting of MORB (Fig. 3b), 93% of these rock samples occupied OIB setting.

Because the required chemical data for all five trace elements (La, Sm, Nb, Yb and Th) were not available for any of the off-shore rocks, the first set of immobile-element based diagrams of Agrawal *et al*. (2008; Fig. 4; Table 3) could not be applied for these rocks.

Finally, the second set of immobile-element based diagrams of Verma and Agrawal (2011; Fig. 5a,c-e; Table 4) indicated MORB tectonic setting (100%) for these off-shore rocks. When MORB setting is missing from a diagram (Fig. 5b), all these off-shore rock samples occupied IAB setting.

Thus, two sets of major-element based discrimination diagrams of Agrawal *et al*. (2004) and Verma *et al*. (2006; Figs. 2-3; Tables 1-2) and the immobile-trace element based diagrams of Verma *et al*. (2011; Fig. 5; Table 4) indicated the tectonic setting of MORB for off-shore basement rocks of DSDP drilled core locations in the Gulf of California.

We have included in the present database the whole-rock chemical data of three rocks dredged from the locations close to the East Pacific Rise near the mouth of the Gulf of California (Lopez *et al*., 1978; Jochum and Verma, 1996). Lopez *et al*. (1978) have reported that these rocks are geochemically similar to other samples from the East Pacific Rise and surrounding seamounts, and are characterized by sea-water alteration effects. The available whole-rock chemical data of these rocks allowed us to apply only major-element based diagrams (Agrawal *et al*., 2004; Verma *et al*., 2006). All the three rock samples dredged from the sea-floor near the mouth of the Gulf of California occupied the field of MORB setting in these major element based diagrams (Figures 2-3; Tables 1-2). Earlier, Lopez *et al*. (1978) have reported that these samples are clustered in the field of ocean floor basalts in the discrimination diagrams of Pearce and Cann (1973) and Pearce (1975). We have also included in the present work the detailed chemical analysis of the individually sampled three parts (the inner less altered "core", the outer more altered "margin" and "glass" from the outer part) of each of these three dredged rocks (Jochum and Verma, 1996). The available geochemical data for these three parts of each of three dredged rocks allowed us to apply only the set of immobile element based diagrams of Agrawal *et al*. (2008). These diagrams indicated a MORB setting for inner less altered "core" and outer altered "margin" parts, and combined island-arc and MORB settings for altered "glass" parts of these three rocks.

Thus, all diagrams – the two sets of new major-element (Agrawal *et al*., 2004; Verma *et al*., 2006) and two sets of trace-element (Agrawal *et al*., 2008; Verma and Agrawal, 2011) based discrimination diagrams – confirm the MORB setting for off-shore rocks. Majority of these off-shore rocks are the basement rocks from the DSDP drilled locations. Concentrations of geochemical elements will be effected by sea-water alteration at these great depths of the oceans as observed in the dredged rocks from the locations close to the East Pacific Rise near the mouth of the Gulf of California (Lopez *et al*., 1978; Jochum and Verma, 1996). In spite of sea-water alteration effects in geochemistry of these three dredged rocks (Lopez *et al*., 1978; Jochum and Verma, 1996), the new tectonomagmatic discrimination diagrams are able to identify their tectonomagmatic origin as MORB. These results show that these four sets of new tectonomagmatic discrimination diagrams may successfully discriminate the original tectonic setting of deep-sea basement rocks and dredged material in spite the possibility of sea-water alteration effects in their geochemical concentrations.

5. Conclusions

The recent discriminant function based discrimination diagrams (Agrawal *et al*., 2004) along with the log-transformed ratios of chemical variables (Verma *et al*., 2006; Agrawal *et al*., 2008; Verma and Agrawal, 2011), in which the tectonic boundaries are determined based on probability estimates, are more powerful and have shown very high success rates in finding the tectonomagmatic origin of on-shore and offshore basic rocks of northwest Mexico. These diagrams have indicated: (1) for on-land basic rocks of <13 Ma age, a continental rift setting (with high success rates); (2) for on-land basic rocks of >13 Ma age, a continental rift setting from major-element based diagrams (with lower success rates than for the younger rocks) and an arc to rift transitional setting from one set of immobile trace-element based diagrams; (3) the only one sample of older age (>13 Ma) from the Comundú arc consistently indicated an arc setting in all diagrams; and (4) MORB setting for off-shore rocks. All these inferred tectonic settings are generally in conformity with those reported in the literature. This work suggests that these new diagrams prepared by relevant statistical methodologies can be successfully applied to infer the tectonic setting of fresh as well as altered basic rocks.

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