Sedimentary Geology 332 (2016) 1–12

Contents lists available at ScienceDirect

Sedimentary Geology

journal homepage: www.elsevier.com/locate/sedgeo

Geochemical discrimination of siliciclastic sediments from active and passive margin settings

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ARTICLE INFO

Article history:
Received 21 August 2015
Received in revised form 20 November 2015
Accepted 21 November 2015
Available online 28 November 2015

Editor: Dr. J. Knight

Keywords:
Sedimentary rocks
Isometric log-ratio transformation
Provenance
Tectonic setting
Discriminant function

ABSTRACT

Discrimination of active and passive margins is important from both academic and economic aspects. This can only be successfully achieved, however, if there are major compositional differences among sediments derived from different continental margins. A worldwide database of active and passive margin settings was established from published major and trace element geochemical data of Neogene to Quaternary siliciclastic sediments. These data were used to evaluate the performance of existing discrimination diagrams, which were shown to work unsatisfactorily with success values of mostly between 0% and 30%. Because these diagrams were not based on a statistically coherent methodology, we proposed two new discriminant functions from linear discriminant analysis of multinormally distributed isometric log-transformed ratios of major and combined major and trace elements. These new diagrams showed very high percent success values of about 87%–97% and 84%–86% for the active and passive margins, respectively, for the original database. Excellent performance of the multidimensional diagrams and related discriminant functions was confirmed from 11 test studies involving Quaternary to Holocene siliciclastic sediments from known tectonic margins. The expected result of an active or passive margin was obtained, with most samples plotting correctly in the respective field.

1. Introduction

It is obvious to assign an active or a passive margin setting to a present-day coastal area. For example, the west coast of South America is an active margin whereas the east coast of the United States is a passive margin. However, it is not so easy to decipher the type of oceanic margin for older Mesozoic to Precambrian sedimentary rocks, especially from the interior of continents. Discrimination of these two types of margins in the past is an important issue from both academic and economic aspects (e.g., Burk and Drake, 1974; Dickinson and Suczek, 1979; Bhatia and Crook, 1986; Weltje, 2006; Assaad, 2009).

Thus, deciphering active or passive margin from sedimentary rock geochemistry has been of much interest (e.g., Dostal and Keppie, 2009; Guadagnin et al., 2015; Zaid, 2015; Zaid et al., 2015; Zhou et al., 2015). Provenance studies based on petrography (e.g., Dickinson and Suczek, 1979; Critelli et al., 1995; Ingersoll and Eastmond, 2007) and geochemistry (e.g., Cullers, 1994, 2000, 2002; Lee et al., 2005, 2015; Surpless, 2014; Perri et al., 2015) of clastic sediments are common. As an advancement in provenance studies, Garzanti et al. (2015) and von Eynatten and Dunkl (2012) addressed the importance of accessory minerals to identify the source rock characteristics of clastic sediments. However, to infer the tectonic setting of a sedimentary basin, researchers are still using the conventional discrimination diagrams of Bhatia (1983), Roser and Korsch (1986), and Bhatia and Crook (1986), even though many studies focussed on sediment geochemistry indicate that these diagrams do not perform satisfactorily (e.g., Armstrong-Altrin and Verma, 2005; Weltje, 2006; Ryan and Williams, 2007; von Eynatten et al., 2012).

The use of compositional data in such bivariate and ternary diagrams poses serious closer and constant sum problems (e.g., Chayes, 1960; Butler, 1979; Aitchison, 1984, 1986). Furthermore, the errors or uncertainties of analytical data invariably present in all experiments are shown to be highly distorted and visually subdued or expanded in ternary diagrams (Verma, 2012, 2015). These problems have been solved by log-ratio transformations (e.g., Aitchison, 1986; Egozcue et al., 2003; Aitchison and Egozcue, 2005; Verma, 2015).

Further, other problems such as eye-fitted discrimination field boundaries and lack of representativeness of some geographical areas also exist in old diagrams (e.g., Agrawal, 1999; Agrawal and Verma, 2007; Verma, 2010).

Nevertheless, because the diagrams by Bhatia (1983), Roser and Korsch (1986), and Bhatia and Crook (1986) are the only tool available for the discrimination of active and passive margin settings, and many studies have cautioned against such diagrams, their performance should be evaluated from similar rock types of known tectonic settings. If these diagrams were found to perform unsatisfactorily, new alternatives are certainly required, which must be proposed from an extensive

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http://dx.doi.org/10.1016/j.sedgeo.2015.11.011
0037-0738/

Table 1
Sample locations for the database construction (M = major; T = trace).

Site no. (Fig. 1)	Location			Age	No. of samples					Reference
					Leg	All samples		Normally distributed samples		
	Country	Longitude	Latitude			M	T	M	T	
Active margin										
1a	Aleutian	161°20′W	52°57′N	Neogene	DSDP 183	31	3	30	3	Plank and Langmuir (1998)
1b	Alaska	147°13′W	56°95′N	Neogene	DSDP 178	2	2	2	2	Plank and Langmuir (1998)
1c	Mexico	99°17′W	15°85′N	Neogene	DSDP 487	3	3	1		Plank and Langmuir (1998)
1d	Guatemala	91°03′W	12°49′N	Neogene	DSDP 495	1	1	1		Plank and Langmuir (1998)
1e	Sandwich	23°21′W	51°98′S	Neogene	ODP 701	12	1	11		Plank and Langmuir (1998)
1f	Antilles	58°65′W	15°71′N	Neogene	DSDP 543	10	2	8		Plank and Langmuir (1998)
1 g	Puerto Rico	65°88′W	19°83′N	Neogene		2		2		Plank and Langmuir (1998)
1 h	Andaman	92°05′E	9°1′S	Neogene				2		Plank and Langmuir (1998)
1i	Java	102°69′E	9°77′S	Neogene	DSDP 211			3	1	Plank and Langmuir (1998)
1j	Java	117°89′E	12°94′S	Neogene	DSDP 261			3	1	Plank and Langmuir (1998)
1 k	Sumatra	102°7′E	9°76′S	Neogene				1	1	Plank and Langmuir (1998)
1 l	Sunda	117°9′E	12°95′S	Neogene				8		Plank and Langmuir (1998)
1 m	Indian Ocean	39°73′E	34°75′S	Neogene				1		Plank and Langmuir (1998)
1n	Hawai	166°97′W	16°48′N	Neogene				1		Plank and Langmuir (1998)
1o	Tonga	165°65′W	23°85′S	Neogene	DSDP 596			6		Plank and Langmuir (1998)
1p	Vanuatu	166°22′E	16°32′S	Neogene				1		Plank and Langmuir (1998)
1q	Japan	134°93′E	32°35′N	Neogene	ODP808			2	1	Plank and Langmuir (1998)
1r	Kurile	153°83′E	38°62′N	Neogene	DSDP 579			2		Plank and Langmuir (1998)
1 s	Kurile	159°79′E	43°92′N	Neogene	DSDP 581			1		Plank and Langmuir (1998)
2a	Aleutian	147°13′W	56°95′N	Pleistocene	DSDP 18-178	13		12		Donnelly (1980)
2b	Aleutian	161°21′W	52°56′N	Pleistocene	DSDP 19-183	34		24		Donnelly (1980)
2c	Peru	81°9′E	12°01′S	Pleistocene	DSDP 34-321	6		3		Donnelly (1980)
2d	Chile bottom	79°41′W	60°01′S	Pleistocene	DSDP 35-322	22		20		Donnelly (1980)
2e	Falkland Island	36°66′W	49°81′S	Pleistocene	DSDP 36-328B	12		11		Donnelly (1980)
2f	Chile Antarctica	73°66′E	65°05′S	Pleistocene	DSDP 35-325	11		11		Donnelly (1980)
2 g	Japan	134°16′E	30°86′N	Pleistocene	DSDP 31-297	14		14		Donnelly (1980)
2 h	Kamchatka	164°71′E	53°01′N	Pleistocene	DSDP 19-192	21		19		Donnelly (1980)
2i	Kamchatka	168°18′E	56°95′N	Pleistocene	DSDP 19-191	10		10		Donnelly (1980)
3	Mexico	104°13′W	18°95′N	Quaternary	Colima	33	33	20	11	Carranza-Edwards et al. (2009)
4a	Mexico	104°32′W	19°10′N	Quaternary	Acapulco	5		4		Hidalgo-Moral (2015)
4b	Mexico	100°01′W	16°91′N	Quaternary	Zihuatanejo	10		3		Hidalgo-Moral (2015)
5	Mexico	99°10′W	15°51′N	Neogene	487–488	34		13		Verma (2000)
6	Chile	74° 81′W	39°90′S	Quaternary	Chile trench	21	14	21	14	Lucassen et al. (2010)
7a	Chile trench	75°85′W	45°89′S	Quaternary	ODP 141	20	20	20	20	Kilian and Behrmann (2003)
7b	Antarctic Plate	80°28′W	51°94′N	Quaternary	ODP 141	8		6		Kilian and Behrmann (2003)
8	Antarctica	58° 09′W	62° 50′S	Quaternary	Bransfield Strait	34		30		Lee et al. (2005)
9a	Antilles	58°63′W	15°71′N	Miocene	DSDP78A-543	12		12		Carpentier et al. (2009)
9b	Antilles	54°34′W	9°45′N	Oligocene E	DSDP14-144A	1		1		Carpentier et al. (2009)
10	Kamchatka	152°97′–171°85′E	37°94′–45°68′N	Miocene	Kurile	9	5	9	4	Bailey (1993)
11a	Japan	144°10′E	39°74′N	Pliocene	DSDP 56-434	54		49		Sugisaki (1980a)
11b	Japan	143°79′E	39°73′N	Pliocene	DSDP 56-435	24		22		Sugisaki (1980a)
11c	Japan	145°55′E	39°93′N	Pliocene	DSDP 56-436	64		60		Sugisaki (1980a)
11d	Japan	143°23′E	40°62′N	Pliocene	DSDP 57-438	51		49		Sugisaki(1980a)
11e	Japan	143°31′E	40°62′N	Pliocene	DSDP 57-439	11		11		Sugisaki (1980a)
11f	Japan	143°92′E	39°73′N	Pliocene	DSDP 57-440	37		36		Sugisaki(1980a)
11 g	Japan	144°07′E	39°75′N	Pliocene	DSDP 57-441	10		10		Sugisaki(1980a)
12a	Japan Trench	143°95′E	40°46′N	PlioceneL	DSDP 87-584	19		13		Minai et al. (1986)
12b	Japan	133°91′E	31°77′N	Quaternary	DSDP87-582	10		10		Minai et al. (1986)
12c	Japan	134°16′E	30°87′N	Pleistocene	DSDP87-297	2		2		Minai et al. (1986)
12d	Japan	133°85′E	31°82′N	Quaternary	DSDP 87-583	19		18		Minai et al. (1986)
13a	Japan Basin	135°33′E	37°06′N	Pleistocene	ODP 128-798	19		19		Minai et al. (1992)
13b	Japan	134°44′E	39°03′N	Pliocene	ODP 128-799	47		17		Minai et al. (1992)
14	Mariana Trench	143°35′E	31°34′N	Quaternary	OPD 185-1149	68		49		Plank et al. (2000)
15	Bonin Trench	141°73′E	30°90′N	Miocene	ODP 125	25	25	23	16	Heling et al. (1992)
16	Bonic Arc	140°00′E	30°92′N	Pleistocene	OPD 126	124		96		Hiscott and Gill (1992)
17a	Japan	136°05′E	28°98′N	Miocene	DSDP 58-442A	90		84		Sugisaki (1980b)
17b	Japan	137°44′E	29°32′N	Pleistocene	DSDP 58-443	318		304		Sugisaki (1980b)
17c	Japan	137°68′E	28°63′N	Miocene	DSDP 58-444	141		139		Sugisaki (1980b)
18	Japan Arc	134°94′E	32°35′N	Quaternary	OPD 131-808A	178	177	173	161	Pickering et al. (1993)
19a	Izu–Bonin	140°00′E	30°92′N	Pliocene	ODP 126-788D	2		2		Gill et al. (1994)
19b	Izu–Bonin	140°37′E	30°39′N	Miocene	ODP 126-792E	4		1		Gill et al. (1994)
19c	Izu–Bonin	140°88′E	31°10′N	Oligocene	ODP 126-793B	1		1		Gill et al. (1994)
20	New Zealand	176°22′E	40°89′S	Miocene	Castlepoint	54	15	29	3	Korsch et al. (1993)
21	Papua	151°57′E	9°18′S	Pleistocen	180–1115	53	49	37	3	Robertson and Sharp (2002)
22a	Philippines	123°50′E	4°79′N	Pleistocene–Miocene	ODP124-767	47	47	47	42	Brass et al. (1991)
22b	Philippines	121°21′E	8°00′N	Pleistocene–Miocene	ODP124-768	86	86	79	60	Brass et al. (1991)