Chemical Geology 355 (2013) 117–133

Contents lists available at ScienceDirect

Chemical Geology

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

New multi-dimensional diagrams for tectonic discrimination of siliciclastic sediments and their application to Precambrian basins

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ARTICLE INFO

Article history:
Received 5 April 2013
Received in revised form 12 July 2013
Accepted 17 July 2013
Available online 26 July 2013

Editor: David R. Hilton

Keywords:
Discrimination diagrams
Arc
Continental rift
Collision
Tectonic setting
Sandstone

ABSTRACT

Siliciclastic sediments owe their origin mainly to land sources. New discriminant-function-based major-element diagrams for the tectonic discrimination of siliciclastic sediments from three main tectonic settings: island or continental arc, continental rift, and collision, have been constructed for the tectonic discrimination of high-silica [$(SiO_2)_{adj}$ = 63%–95%] and low-silica rocks [$(SiO_2)_{adj}$ = 35%–63%], where $(SiO_2)_{adj}$ refers to the SiO_2 value obtained after volatile-free adjustment of the ten major-elements to 100 wt.%. These diagrams are based on worldwide examples of Neogene–Quaternary siliciclastic sediments from known tectonic settings, $\log_e$-ratio transformation of ten major-elements with SiO_2 as the common denominator, and linear discriminant analysis of the $\log_e$-transformed ratio data. The success rates of these diagrams as judged from the original data varied from 84.5% to 93.6%. These diagrams were successfully tested on Neogene to Quaternary rocks not included in the original database. These discriminant diagrams were also successfully applied on older high-silica and low-silica sandstones and shales of Paleoarchean–Ediacaran age. Finally, these diagrams were shown to be useful against chemical changes related to analytical errors, weathering, recycling and post-depositional processes.

1. Introduction

Continents have split and have reassembled through the Earth's history. Extensional processes within continents give rise to continental rifts. With increased extension, "thinning" of the continental crust surrounding the rift takes place and eventually the extension then occurs in the oceans with the generation of new oceanic crust. These extensional areas in the oceans become mid-ocean ridges and the process generates ocean floor spreading. Eventually, the two margins separated by an ocean are called passive margins. Elsewhere in the oceans, subduction processes take place beneath continental and oceanic plates giving rise to continental and island arc volcanism, respectively. Oceanic plates may eventually be totally consumed beneath continents and continent–continent collision may take place. Thus, besides the mid-ocean ridge tectonic setting, these tectonic processes give rise to three main tectonic settings: island arc or continental arc, continental rift, and continental collision.

This brief description may sound quite simplistic and even unnecessary. Ironically, it has not been explicitly used so far in the study of sedimentary rocks. Siliciclastic sediments are commonly derived from continental sources and usually form near or in continental blocks away from deep oceans. The chemical composition of silica-rich rocks having $(SiO_2)_{adj} > 35\%$, may be controlled by plate tectonic processes, specifically sandstone compositions are governed by such processes (Dickinson and Suczek, 1979).

Provenance studies are common for sedimentary rocks (Cullers, 2000, 2002; Armstrong-Altrin et al., 2004, 2012, 2013; Ohta, 2008; Chakrabarti et al., 2009; Singh, 2009, 2010; Bakkiaraj et al., 2010; van de Kamp, 2010; Etemad-Saeed et al., 2011; Saxena and Pandit, 2012; Ingersoll et al., 2013), which clearly show that much greater emphasis is placed on the provenance rather than on the plate tectonic processes. Some believe that appropriate plate tectonic inferences cannot be made from the study of sedimentary rocks, because the provenance may affect the chemical compositions to the extent that plate tectonic implications will not be discernible. Thus, because of the multivariate (multi-factor) nature of the problem, especially the effects of sedimentary provenance (source rocks, their lithology, tectonic setting, the climate, and the relief and slope of the source areas), some workers have expressed serious doubts on the possibility of discriminating tectonic setting from chemical means (e.g., Ryan and Williams, 2007; Pe-Piper et al., 2008; von Eynatten and Dunkl, 2012). Therefore, plate tectonic inferences from sedimentary rocks are not carried out in terms of these tectonic settings in spite of the fact that such inferences are now commonly obtained from multi-dimensional tectonomagmatic discrimination diagrams for igneous rocks (Verma et al., 2006, 2013; Sheth, 2008; Verma, 2010, 2012a, 2013; Verma and Verma, in press; Pandarinath and Verma, 2013; Verma and Oliveira, 2013).

The major-element compositions based on tectonic setting discrimination diagrams proposed by Bhatia (1983) and Roser and Korsch

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http://dx.doi.org/10.1016/j.chemgeo.2013.07.014

Table 1
Sample locations for the database construction. Arc — island or continental arc; Rift — continental rift; Col — collision; HStr — high-silica training set; HSte — high-silica testing set; LStr — low-silica training set; LSte — low-silica testing set.

Site no. (Fig. 1)	Tectonic setting	Location			Age	No. of samples				Reference
		Country	Longitude	Latitude		HStr	HSte	LStr	LSte	
1	Arc	Kamchatka	158°14′E–161°29′E	39°7′N–52°11′N	Miocene	5	1	2	1	Bailey (1993)
2a	Arc	Kamchatka	161°29′E	47°06′N	Neogene	1				Plank and Langmuir (1998)
2b	Arc	Kurile	159°48′E	43°56′N	Neogene	2		1		Plank and Langmuir (1998)
2c	Arc	Japan	134°56′E	32°21′N	Neogene	3				Plank and Langmuir (1998)
2d	Arc	Ryuku	131°22′E	22°34′N	Neogene			1		Plank and Langmuir (1998)
2e	Arc	Philippines	127°50′E	12°48′N	Neogene			1		Plank and Langmuir (1998)
2f	Arc	Mariana	156°22′E	18°39′N	Neogene	4		2	1	Plank and Langmuir (1998)
2 g	Arc	Vanuatu	166°22′E	16°32′S	Neogene			1		Plank and Langmuir (1998)
2 h	Arc	Tonga	165°39′W	23°51′S	Neogene	5		20	3	Plank and Langmuir (1998)
2i	Arc	Sunda	117°54′E	12°57′S	Neogene	2		9		Plank and Langmuir (1998)
2j	Arc	Sumatra	102°42′E	9°46′S	Neogene		1			Plank and Langmuir (1998)
2 k	Arc	Java	102°42′E	9°47′S	Neogene	5		1		Plank and Langmuir (1998)
2 l	Arc	Andaman	92°03′E	09°06′S	Neogene	2				Plank and Langmuir (1998)
2 m	Arc	Makran	59°42′E	16°28′N	Neogene			1		Plank and Langmuir (1998)
2n	Arc	Sandwich	23°12′W	51°59′S	Neogene	10		1	1	Plank and Langmuir (1998)
2o	Arc	Southern Antilles	52°10′W	14°15′N	Neogene			1		Plank and Langmuir (1998)
2p	Arc	Antilles	58°39′W	15°42′N	Neogene	1		8		Plank and Langmuir (1998)
2q	Arc	Puerto Rico	66.83°W	19.55°N	Neogene			2		Plank and Langmuir (1998)
2r	Arc	Peru	82°32′W	9°40′S	Neogene			1		Plank and Langmuir (1998)
2 s	Arc	Guatemala	91°2′W	12°30′N	Neogene	1				Plank and Langmuir (1998)
2 t	Arc	Central Pacific	136.18°′W	9.80°N	Neogene			1		Plank and Langmuir (1998)
2u	Arc	Alaska	147°07′W	56°57′N	Neogene	2				Plank and Langmuir (1998)
2v	Arc	Aleutian	161°12′W	52°34′N	Neogene	15	1	15		Plank and Langmuir (1998)
3	Arc	Japan	143°57′E	40°28′N	Pliocene	16	1			Minai et al. (1986)
4	Arc	Japan	143°14′E	40°38′N	Pliocene	48	3			Sugisaki (1980)
5	Arc	Japan	143°19′E	40°38′N	Pliocene	10	1			Sugisaki (1980)
6	Arc	Japan	140°57′E	38°9′N	Holocene	6		1		Igarashi et al. (2007)
7	Arc	Japan	132°57′E	35°26′N	Holocene	45	1			Ishiga et al (2000)
8	Arc	Mariana	143°21′E	31°21′N	Quaternary to Miocene			8	1	Plank et al. (2000)
9	Arc	Japan	140°45′E	32°23′N	Holocene to Miocene	57	4	58	5	Hiscott and Gill (1992)
10	Arc	Japan	143°21′E	31°21′N	Quaternary	53	3			Plank et al. (2007)
11a	Arc	Izu–Bonin	139°51′E	30°46′N	Pleistocene			1		Gill et al. (1994)
11b	Arc	Izu–Bonin	140°22′E	30°55′N	Pliocene			2		Gill et al. (1994)
11c	Arc	Izu–Bonin	140°23′E	30°24′N	Miocene to Oligocene			3	1	Gill et al. (1994)
11d	Arc	Izu–Bonin	140°53′E	31°6′N	Miocene to Oligocene			1		Gill et al. (1994)
11e	Arc	Izu–Bonin	139°52′E	30°55′N	Pleistocene			1		Gill et al. (1994)
12	Arc	Japan	134°57′E	32°21′N	Pliocene to Quaternary	111	3	2	1	Pickering et al. (1993)
13	Arc	Philippines	120°57′E	15°30′N	Quaternary	8		59	2	Liu et al. (2009)
14a	Arc	Papua New Guinea	150°9′E	6°14′S	Recent			13		Whitmore et al. (2004)
14b	Arc	Papua New Guinea	147°36′E	6°42′S	Recent			1		Whitmore et al. (2004)
14c	Arc	Papua New Guinea	147°48′E	6°21′S	Recent			5	1	Whitmore et al. (2004)
14d	Arc	Papua New Guinea	147°6′E	6°40′S	Recent			50	4	Whitmore et al. (2004)
15	Arc	New Zealand	168°38′E	44°57′S	Quaternary	67	2	2	1	Kautz and Martin (2007)
16	Arc	Bransfield Strait	58°6′W	62°31′S	Quaternary	12		22		Lee et al. (2005)
17	Arc	King George Island	58°46′W	62°12′S	Recent	3		24	3	Lee et al. (2004)
18a	Arc	Chile	74°48′W	39°54′S	Quaternary	1				Lucassen et al. (2010)
18b	Arc	Chile	74°5′W	36°4′S	Quaternary			2		Lucassen et al. (2010)
18c	Arc	Chile	74°58′W	38°31′S	Quaternary			1	1	Lucassen et al. (2010)
18d	Arc	Chile	74°48′W	39°51′S	Quaternary			2		Lucassen et al. (2010)
18e	Arc	Chile	74°25′W	36°45′S	Quaternary			2		Lucassen et al. (2010)
18f	Arc	Chile	74°42′W	38°19′S	Quaternary			2		Lucassen et al. (2010)
18 g	Arc	Chile	74°49′W	39°56′S	Quaternary			1		Lucassen et al. (2010)
18 h	Arc	Chile	74°37′W	38°44′S	Quaternary			1		Lucassen et al. (2010)
18i	Arc	Chile	74°11′W	36°39′S	Quaternary			0	1	Lucassen et al. (2010)
18j	Arc	Chile	74°12′W	36°40′S	Quaternary			1		Lucassen et al. (2010)
18 k	Arc	Chile	74°30′W	38°5′S	Quaternary			2		Lucassen et al. (2010)
18 l	Arc	Chile	74°51′W	39°54′S	Quaternary			0	1	Lucassen et al. (2010)
18 m	Arc	Chile	74°46′W	39°37′S	Quaternary			1		Lucassen et al. (2010)
18n	Arc	Chile	74°10′W	36°58′S	Quaternary			2		Lucassen et al. (2010)
19	Arc	Antilles	58°38′W	15°43′N	Miocene	1		2	1	Carpentier et al. (2009)
20	Arc	Mexico	92°32′W	14°49′N	Quaternary			1		Carranza-Edwards et al. (2001)
21	Arc	Kermadec	174°7′W	24°57′S	Miocene			5	1	Ewart et al. (1998)
22	Arc	Tonga–Kermadec	178°25′W	41°40′S	Quaternary	4	2	4		Gamble et al. (1996)
23	Rift	Mexico	114°00′W	28°03′N	Recent	11				Kasper-Zubillaga and Zolezzi-Ruiz (2007)
24	Rift	California	121°6′W	34°32′N	Quaternary			16	1	Tada et al. (2000)
25	Rift	Colorado	105°46′W	39°33′N	Recent			10	1	van de Kamp and Leake (1985)
26a	Rift	Mexico	97°11′W	20°44′N	Recent	5		3		Armstrong-Altrin (2009)
26b	Rift	Mexico	111°57′W	28°50′N	Recent	4		1		Armstrong-Altrin (2009)
27	Rift	Brazil	53°54′W	2°01′S	Pleistocene	50	4			Vital and Stattegger (2000)
28	Rift	Spain	6°57′W	37°15′N	Holocene	32	1	21		Borrego et al. (2002)
29	Rift	Spain	7°18′W	37°10′N	Holocene	6		9		Sánchez-García et al. (2010)