

## Provenance of sands from Cazonos, Acapulco, and Bahía Kino beaches, México

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### ABSTRACT

*Petrographic, major, trace, and rare-earth element geochemistry of sands from three beaches of México (Cazonos, Acapulco, and Bahía Kino) were studied to determine their provenance. The textural study reveals that the proportion of quartz is higher in Bahía Kino (~48–83 %) than in Cazonos (~22–48 %) and Acapulco (~20–48 %) sands. Most of the sand samples are classified as felsic sands using  $\text{SiO}_2$  content. The variations in  $\text{SiO}_2$ ,  $\text{Fe}_2\text{O}_3$ ,  $\text{MgO}$ ,  $\text{TiO}_2$  contents and  $\text{Al}_2\text{O}_3/\text{TiO}_2$ ,  $\text{K}_2\text{O}/\text{Na}_2\text{O}$ ,  $\text{SiO}_2/\text{Al}_2\text{O}_3$  ratios among the three study areas reflect differences in source rock characteristics. The low Chemical Index of Alteration values (CIA: ~38–58) suggest the prevalence of weak weathering conditions in the source regions. A steady weathering trend identified in the A-CN-K diagram for Acapulco and Cazonos sands is indicative of uplift along the source region and indicates that sands were derived from diverse sources. A major variation in  $\Sigma\text{REE}$  content is observed in Acapulco sands (~22–390 ppm) than in Cazonos (~49–83 ppm) and Bahía Kino sands (~50–89 ppm), and is likely due to differences in fractionation of minerals. However, all the sand samples show similar REE patterns with enriched LREE, depleted HREE and a negative Eu anomaly. The comparison of REE data of sands with those of source rocks located relatively close to the study areas suggest that Cazonos and Acapulco sands were derived from felsic and intermediate rocks, whereas Bahía Kino sands were derived from felsic rocks.*

*Key words: beach sand, provenance, weathering, geochemistry, hydraulic sorting, tectonic settings, zircon, ilmenite, rare-earth elements, Bahía Kino, Cazonos, Acapulco, Mexico.*

### RESUMEN

*La petrografía y geoquímica de elementos mayores, traza y de tierras raras de arenas de tres playas de México (Cazonos, Acapulco y Bahía Kino) fueron estudiadas para determinar su procedencia. El estudio textural revela que la proporción del cuarzo en las arenas es mayor en Bahía Kino (~48–83 %) que en Cazonos (~22–48 %) y en Acapulco (~20–48 %). La mayoría de las muestras de arenas son clasificadas como arenas félsicas de acuerdo con su contenido de  $\text{SiO}_2$ . Las variaciones en el contenido de  $\text{SiO}_2$ ,  $\text{Fe}_2\text{O}_3$ ,  $\text{MgO}$ ,  $\text{TiO}_2$  y las relaciones  $\text{Al}_2\text{O}_3/\text{TiO}_2$ ,  $\text{K}_2\text{O}/\text{Na}_2\text{O}$ ,  $\text{SiO}_2/\text{Al}_2\text{O}_3$  determinadas en las tres áreas de estudio reflejan diferencias en las características de la roca fuente. Los bajos valores en el Índice de Alteración Química (CIA: ~38–58) sugieren la prevalencia de condiciones de bajo intemperismo en las regiones de las rocas fuente. La estable tendencia de intemperismo identificada en el diagrama A-CN-K para las arenas de Acapulco y Cazonos indica un levantamiento de la región de la fuente, por lo que se deduce que las arenas se derivaron de diversas fuentes. Una mayor variación en los contenidos de  $\Sigma\text{REE}$  es observada en las arenas de Acapulco (~22–390 ppm) que en Cazonos (~49–83 ppm) y que en las arenas de Bahía*

*Kino (~50–89 ppm), lo que se debe probablemente a diferencias en el fraccionamiento de minerales. Sin embargo, todas las muestras de arena presentan patrones similares REE con enriquecimiento de LREE, empobrecimiento de HREE y una anomalía negativa de Eu. La comparación de los datos de REE de las muestras con los obtenidos para la roca fuente, localizada relativamente cerca del área de estudio, sugiere que las arenas de Cazones y Acapulco fueron derivadas de rocas félsicas e intermedias, mientras que las arenas de Bahía Kino se derivaron sólo de rocas félsicas.*

*Palabras clave: arena de playa, procedencia, intemperismo, geoquímica, clasificación hidráulica, ambientes tectónicos, circón, ilmenita, elementos de las Tierras Raras, Bahía Kino, Cazones, Acapulco, México.*

## INTRODUCTION

It is well known that the tectonic, climatic and magmatic history of continents is partly retained in clastic sediments. Important in extracting this information are lithologic association, detrital mineralogy, and chemical composition (e.g., Condie *et al.*, 2001; Zimmermann and Spalletti, 2009). In general, the original composition of weathered source rocks exerts a dominant control on the formation of clastic sediments. Therefore, geographic and stratigraphic variations in provenance can provide important constraints on the tectonic evolution of a region (e.g., McLennan *et al.*, 1993; Condie *et al.*, 2001; LaMaskin *et al.*, 2008). To evaluate the provenance and tectonic setting of clastic sediments, geochemical approaches are more suitable than petrographic analyses based on framework modes (Liu *et al.*, 2007). The relations between provenance and basins are also governed by plate tectonics, which thus ultimately control the different types of sediments (Dickinson and Suczek, 1979). However, in recent years, tectonic discrimination based on major elements has received considerable criticism (Zimmermann, 2005; Armstrong-Altrin and Verma, 2005; Weltje, 2006; Ryan and Williams, 2007; Jafarzadeh and Hosseini-Barzi, 2008; Borges *et al.*, 2008; Achurra *et al.*, 2009; Gosen *et al.*, 2009), whereas schemes that depend on trace elements have been considered relatively reliable (Cingolani *et al.*, 2003; Campo and Guevara, 2005; LaMaskin, *et al.*, 2008). Considering the previous studies on beach sands of Mexico, Armstrong-Altrin and Verma (2005) used geochemical data of Neogene sediments from the Gulf of Mexico and the Pacific coast of Mexico to evaluate the previously proposed tectonic setting discrimination diagrams, which resulted in poor discrimination. Therefore, in the present work it is not recommended to use this kind of tectonic discrimination; besides, there are other problems in its use (see below).

Some authors have analyzed the textural characteristics of beach sands along the coastal regions of Mexico (Marsaglia, 1991; Carranza-Edwards and Rosales-Hoz, 1995; Carranza-Edwards *et al.*, 1998, 2009; Carranza-Edwards, 2001; Kasper-Zubillaga and Dickinson, 2001; Okazaki *et al.*, 2001; Kasper-Zubillaga and Carranza-Edwards, 2005; Madhavaraju *et al.*, 2009). These studies described clearly the grain size and textural differences among different depositional environments. Other studies

on geochemistry of beach sands of Mexico are focused on heavy metals (Rosales-Hoz and Carranza-Edwards, 1998; Rosales-Hoz *et al.*, 1999, 2003). On the basis of geochemistry of beach sands in the western Gulf of Mexico, Kasper-Zubillaga *et al.* (1999) suggested that the geochemistry of beach sands are highly useful to identify the tectonic setting of a sedimentary basin. Carranza-Edwards *et al.* (2001) concluded that the REE, Th, Sc, and Hf concentrations in beach sands of western Mexico are associated with source rock composition than to heavy minerals. Recent studies by Kasper-Zubillaga *et al.* (2008a, 2008b) discussed about the textural and geochemical discriminations between desert and coastal dune sands of northwestern Mexico.

The purpose of this study is to evaluate the geochemical discriminations among the three beach areas and to investigate their source rocks. To identify the probable source rocks, the geochemical data of these sands are compared with dacite, rhyolite, granite, granodiorite, andesite, basaltic andesite, and basalts from areas located relatively close to the study areas (see Figure 1 for locations, rock types, and sources). The comparison was made individually for the three study areas (Cazones, Acapulco, and Bahía Kino), because they are supposed to receive sediments from totally different sources (Armstrong-Altrin and Verma, 2005; Rosales-Hoz and Carranza-Edwards, 1995; Marsaglia, 1991). In addition, the role played by accessory heavy minerals on the control of trace and rare earth elements (REE) will be also addressed in this paper.

At first sight, it may appear that, because Cazones represents a passive margin setting, Acapulco an active margin setting, and Bahía Kino a rifted margin setting, it might be worthwhile to evaluate the geochemical data through discrimination diagrams. However, the provenance of Cazones sands resides in the eastern part of the Mexican Volcanic Belt (MVB) and the Eastern Alkaline province, both of which seem to contain rocks of an extensional setting (Verma, 2004, 2006; Robin, 1982a). The same is the case of Bahía Kino where rocks of the rifted margin are extensively exposed (Spencer and Normark, 1979; Paz-Moreno and Demant, 1999; Conly *et al.*, 2005). For the Acapulco area, generally characterized as an active margin, the provenance of beach sands could be as far as the MVB (Sierra Chichinautzin in Figure 1). However, there has been a controversy regarding the origin of the volcanism in the

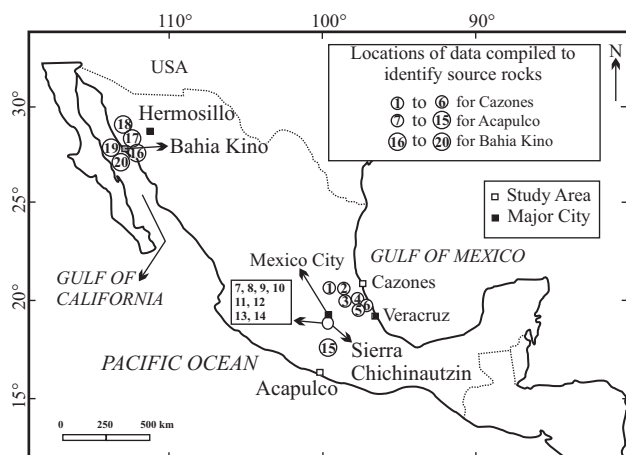


Figure 1. Map showing study areas and locations of the source areas from where the geochemical data are compiled in this study to identify probable source rocks (map modified after Keppie, 2004). The data sources for provenance of Cazonos are: 1. Verma (2001a), 2. Rosales-Lagarde *et al.* (2005), 3. Verma (2001b), 4. Verma (2000a), 5. Carrasco-Núñez *et al.* (2005), 6. Gómez-Tuena *et al.* (2003); Acapulco: 7. Martínez-Serrano *et al.* (2004), 8. Márquez and Ignacio (2002), 9. Schaaf *et al.* (2005; geochemical data only from Sierra de Chichinautzin volcanic field were taken), 10. Siebe *et al.* (2004), 11. Velasco-Tapia and Verma (2001a), 12. Verma (1999), 13. Verma (2000b), 14. Wallace and Carmichael (1999), 15. Meza-Figueroa *et al.* (2003); Bahía Kino: 16. Valencia-Moreno *et al.* (2003), 17. Valencia-Moreno *et al.* (2001), 18. Vidal-Solano *et al.* (2007), 19. Desonie (1992), 20. Saunders *et al.* (1982) and Saunders (1983). The rock types compiled to identify the provenance of Cazonos are: rhyolite (Verma, 2000a, 2001a, 2001b; number of samples  $n = 10$ ), andesite (Rosales-Lagarde *et al.*, 2005;  $n = 12$ ), basaltic andesite (Verma, 2001a, 2001b;  $n = 9$ ), and basalt (Verma, 2000a, 2001a, 2001b; Gómez-Tuena *et al.*, 2003; Carrasco-Núñez *et al.*, 2005;  $n = 39$ ); Acapulco: dacite (Schaff *et al.*, 2005; Martínez-Serrano *et al.*, 2004; Verma, 1999; Márquez and Ignacio, 2002; Wallace and Carmichael, 1999;  $n = 42$ ), granodiorite (Meza-Figueroa *et al.*, 2003;  $n = 13$ ), andesite (Schaff *et al.*, 2005; Martínez-Serrano *et al.*, 2004; Siebe *et al.*, 2004; Verma, 1999; Márquez and Ignacio, 2002; Wallace and Carmichael, 1999;  $n = 104$ ), basaltic andesite (Schaaf *et al.*, 2005; Martínez-Serrano *et al.*, 2004; Siebe *et al.*, 2004; Velasco-Tapia and Verma, 2001a; Verma, 1999; Márquez and Ignacio, 2002; Wallace and Carmichael, 1999;  $n = 61$ ), and basalt (Schaaf *et al.*, 2005; Siebe *et al.*, 2004; Verma 2000b; Velasco-Tapia and Verma, 2001a; Márquez and Ignacio, 2002; Wallace and Carmichael, 1999;  $n = 54$ ); Bahía Kino: rhyolite (Desonie, 1992; Vidal-Solano *et al.*, 2007;  $n = 32$ ), granite (Valencia-Moreno *et al.*, 2001, 2003;  $n = 40$ ), andesite (Desonie, 1992;  $n = 8$ ), and basalt (Saunders *et al.*, 1982; Saunders, 1983;  $n = 21$ ).

MVB, whether it is related to the same active subduction process (Robin, 1982b; Wallace and Carmichael, 1999; Gómez-Tuena *et al.*, 2007), or it owes its origin to other tectonic mechanisms such as plume influence (Márquez *et al.*, 1999) or extensional setting (Sheth *et al.*, 2000; Verma, 2002). Given the complexity of the on-land geology in Mexico, the application of conventional tectonic discrimination diagrams is a difficult task. Furthermore, the available discrimination diagrams for sediments and sedimentary rocks are not based on the correct statistical methodology as recently done by workers in the field of igneous rock discrimination (Agrawal *et al.*, 2004, 2008; Agrawal and Verma, 2007; Verma, in press). Besides, the use of discrimi-

nation diagrams in the field of sedimentary geology has been discouraged by Ryan and Williams (2007), although Verma (in press) has shown that the new discrimination diagrams based on log-ratio transformation work well for tectonic discrimination of igneous rocks. Therefore, the use of this kind of tools in the study of sediments and sedimentary rocks should wait for new discrimination diagrams.

## STUDY AREAS

The study area Cazonos (Figure 2a), is located in the western part of the Gulf of Mexico (Lat 20°44'N and Long 97°11'W). Sedimentary rocks of the study area are dominated by Tertiary and Quaternary sandstones, and alluvial deposits (Padilla y Sanchez and Aceves-Quesada, 1990). Volcanic rocks are dominated by Miocene-Pliocene andesites of sub-alkaline composition (*e.g.*, Cantagrel and Robin, 1979; Negendank *et al.*, 1985; Verma 2001a, 2001b). The volcanic units of the study area belong to the overlap region of the MVB and the Eastern Alkaline Province (*e.g.*, Verma, 2006). The major river shed near to the study area is Cazonos (Figure 2a).

The study area Acapulco (Figure 2b) is located in southern part of Mexico (Lat 16°50'N and Long 99°56'W). Rocks are dominated by: (1) granites and granitoids of Early Paleocene age; (2) volcanic rocks of intermediate to acid composition, mostly of early Tertiary age (andesite to rhyolite); (3) sedimentary rocks of Mesozoic to Tertiary ages; and (4) Quaternary alluvium. The beach sands of Acapulco receive sediments derived from central part of the MVB (Velasco-Tapia and Verma, 2001a, 2001b; Verma, 2002, 2009a) as well as largely from Guerrero state (Meza-Figueroa *et al.*, 2003; Freydier *et al.*, 2000). In the MVB, igneous rocks from basaltic to rhyolitic compositions have erupted, which may also contribute to the beach sands of Acapulco. The Guerrero terrane (Campa, 1985; Coney, 1989) is composed of Late Jurassic to Early Cretaceous igneous and sedimentary rocks considered to be developed in an intra-oceanic setting (Centeno-Garcia *et al.*, 1993; Tardy *et al.*, 1994). The major river that discharges relatively near to Acapulco beach is Papagayo (Figure 2b).

The study area Bahía Kino (Figure 2c) is located in the Gulf of California, northwestern part of Mexico, and is a semi-closed basin (Lat 28°50'N and Long 111°57'W). The coastal Sonora batholith, located in this part is characterized by continuous exposures of granitic rocks along the NW-SE oriented belt (Valencia-Moreno *et al.*, 2003). The exposed sedimentary rocks are Quaternary alluvium, Early Jurassic quartz arenites, and Tertiary sandstones. The volcanic rocks are andesite and rhyolite types (Desonie, 1992; Vidal-Solano *et al.*, 2007) of early Tertiary age. Among intrusive rocks, granites and granodiorites of Mesozoic age are dominant (Valencia-Moreno *et al.*, 2001, 2003). River San Ignacio is the small river that drains near to the study area Bahía Kino, and major rivers are practically absent.

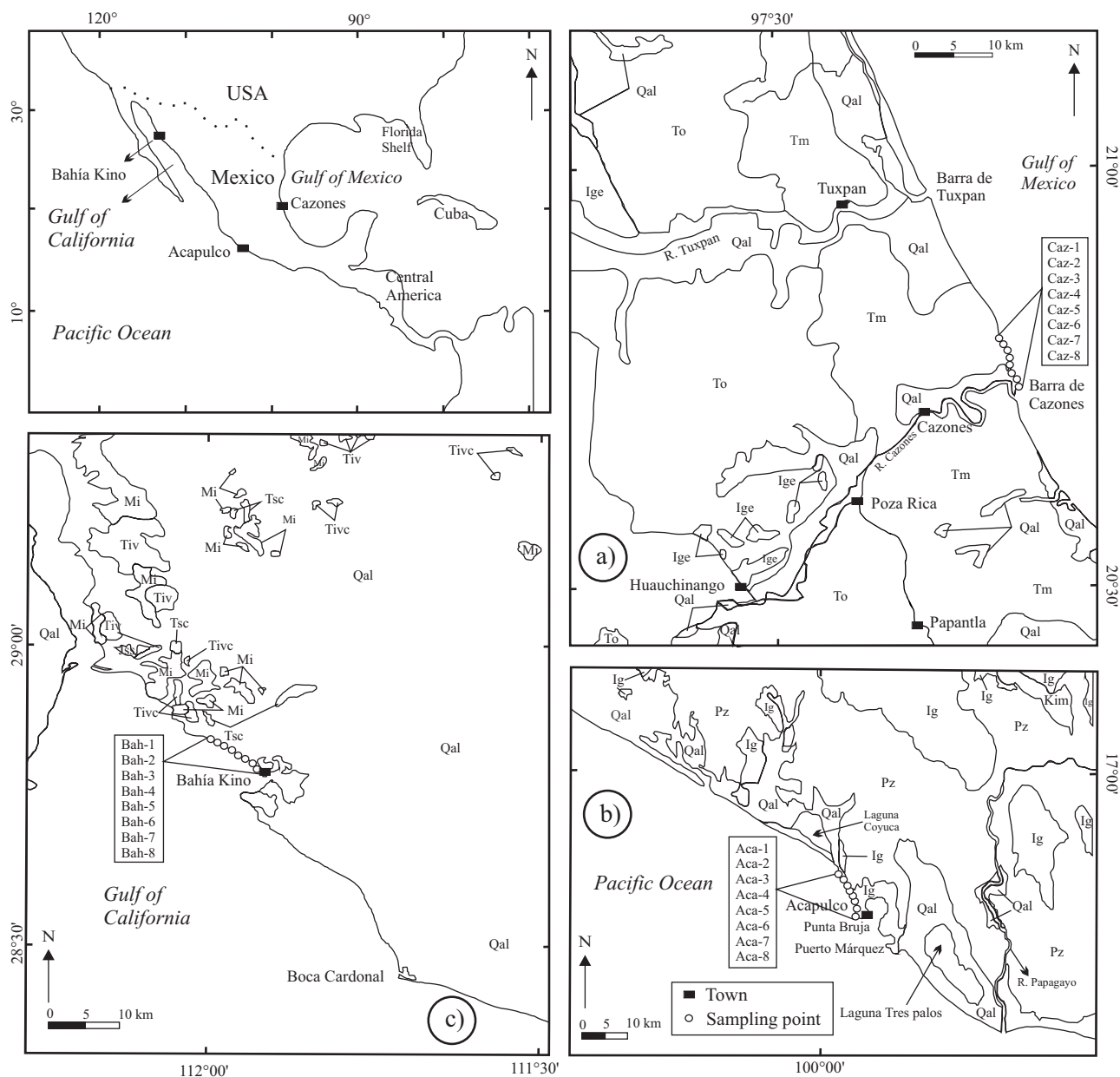


Figure 2. Simplified geological maps of the study areas showing sample locations (map modified from Consejo de Recursos Minerales, 1992, 1994, and 1999). (a) Cazones area; (b) Acapulco area; (c) Bahía Kino area. Volcanic and sedimentary units are: Ig: intrusive igneous rocks; Ige: extrusive igneous rocks (andesite); Jss: sedimentary rocks (lower Jurassic); Mi: intrusive rocks (Mesozoic); Pz: metamorphic rocks (Proterozoic); Qal: alluvium (Quaternary); Tiv: volcanic rocks (lower Tertiary); Tivc: volcanoclastic rocks (lower Tertiary); Tm: marine rocks (Tertiary; sandstone, mudstone); To: sandstone and limestone (Oligocene); Tsc: clastic rocks (upper Tertiary).

## METHODS

Twenty-four surface sand samples (eight samples from Cazones; eight from Acapulco; eight from Bahía Kino) were collected from the uppermost part (20 mm) of the beach, where the waves end. Grain-size analysis was carried out using a Ro-Tap sieve shaker with American Society for Testing and Material (ASTM) sieves ranging from  $\sim 1.5 \phi$  to  $4.25 \phi$  at  $0.50 \phi$  intervals for 20 minutes (Folk, 1966). Modal mineralogical determinations were carried out by counting 200 hundred grains per thin-sections. The point counts were

done using both Gazzi-Dickinson (Gazzi, 1966; Dickinson, 1970) and standard methods. Heavy minerals were separated by the gravitational method and the compositions of different heavy minerals were counted and estimated under a binocular microscope.

All the twenty-four samples were analyzed for major, trace and rare-earth element geochemistry. Major elements were analyzed with a X-ray Fluorescence Spectrometer. The powdered samples, after drying at  $110^\circ\text{C}$  for 6 hours, were calcinated in a muffle at  $1000^\circ\text{C}$  for a couple of hours, for loss on ignition (LOI) determination. For X-ray fluorescence

analyses, fused bead was prepared from each calcinated sample using lithium tetraborate flux. These analyses were performed with a Rigaku unit model RIX-3000 equipped with Rh tube, by using the calibration curve method and international reference materials. The chemical analyses have precisions better than 5 % for all major elements. The major-element data were recalculated on an anhydrous (LOI-free) basis and adjusted to 100 % before using them in various diagrams. For the determination of CaO in the silicate fraction, samples were separately treated with cold HCl 1M before digestion and were analysed separately.

Trace elements, including fourteen rare-earth elements (REE), were determined using a Finningan MAT ELEMENT high resolution inductively coupled plasma mass spectrometer (ICP-MS) at the National Geophysical Research Institute, India, following the methods of Balaram *et al.* (1995), Wu *et al.* (1996), and Yoshida *et al.* (1996). Precision and accuracy for analysis of reference material JG-2, as determined by ICP are compared with data published by Imai *et al.* (1995), are better than  $\pm 1\%$  for Ba, Co, Cu, Ga, Nb, Pb, Rb, Sc, Sr, Y, Zn, Zr, La, Pr, Nd, Sm, Ho, Er, and Lu. The analytical precision for other elements such as Cr, Cs, Hf, Ni, Th, U, V, Eu, Gd, Tb, Dy, and Yb are better than  $\pm 3\%$ , whereas it is better than  $\pm 5\%$  for Tm (Table 1). Similarly, the values are within the 95% confidence interval given in Guevara *et al.* (2001), except for the elements Co, Cr, Cs, Ga, Pb, Sr, Y, Zr, La, Ce, Pr, Gd, Tb, Ho, Er, and Tm (Table 1).

The sand samples were classified according to their adjusted SiO<sub>2</sub> contents [(SiO<sub>2</sub>)<sub>adj</sub>], using measured Fe<sub>2</sub>O<sub>3</sub> concentrations (computer program SINCLAS by Verma *et al.*, 2002), into three categories: mafic (equivalent to basic for igneous rocks); intermediate; and felsic (equivalent to acidic for igneous rocks). The geochemical data were statistically evaluated through the methodology of outlier-based methods (Barnett and Lewis, 1994; Verma, 2005) using the option of single-outlier tests in software DODESYS (S.P. Verma and L. Díaz-González, unpublished), which is based on new precise and accurate critical values recently simulated by Verma and Quiroz-Ruiz (2006a, 2006b, 2008) and Verma *et al.* (2008).

For interpreting the geochemical data from these three areas, a database for source rock geochemistry was constructed from the numerous references (see Figure 1 for locations and more details). Besides, significance *t* and *F* tests were used to compare the data from different areas (Jensen *et al.*, 1997; Verma, 2005, 2009b).

## RESULTS

### Texture and mineralogical composition

Grain size parameters for the three study areas were calculated according to the equation of Folk and Ward (1957) and are given in Table 2. The mean grain size ranges

from  $\sim 1.42 \phi$  to  $3.83 \phi$  for Cazonés sands, suggesting that sand grains are medium to very fine in size. The Acapulco sands are coarse to very fine ( $\sim 0.84$ – $3.90 \phi$ ) and Bahía Kino sands are coarse to medium sizes ( $\sim 0.42$ – $2.00 \phi$ ). Distinct differences in standard deviation (in  $\phi$  units) values are also observed among the three study areas. The standard deviation values of Cazonés vary from  $0.49 \phi$  (well sorted) to  $0.71 \phi$  (moderately well sorted). The Acapulco sands range between moderately sorted ( $0.99 \phi$ ) and poorly sorted ( $1.32 \phi$ ). However, a homogeneous trend is observed in the Bahía Kino sands, which are well sorted ( $\sim 0.38$ – $0.50 \phi$ ).

For the Bahía Kino sands, quartz is the major constituent ( $\sim 48$ – $83\%$ ), followed by feldspar ( $\sim 9$ – $32\%$ ) and lithic fragments ( $\sim 7$ – $24\%$ ). However, sands from Cazonés and Acapulco are slightly higher in lithic fragments than in quartz (Table 2). The average quartz-feldspar-lithic fragment (Qt:Ft:L) ratios are Qt<sub>38</sub>:Ft<sub>19</sub>:LF<sub>43</sub>, Qt<sub>36</sub>:Ft<sub>19</sub>:LF<sub>45</sub>, Qt<sub>63</sub>:Ft<sub>23</sub>:LF<sub>14</sub> for Cazonés, Acapulco, and Bahía Kino sands, respectively. The common accessory heavy minerals identified are zircon, ilmenite, titanomagnetite, and magnetite (Table 3). Among them, zircon is the most abundant mineral identified in Bahía Kino and Cazonés sands. On the other hand, ilmenite and titanomagnetite are the dominant minerals in Acapulco sands.

### Major element geochemistry

Table 4 lists the major element concentrations of analyzed beach sands and are arranged according to increasing (SiO<sub>2</sub>)<sub>adj</sub> content. Although Le Bas *et al.* (1986) did not recommend the use of (SiO<sub>2</sub>)<sub>adj</sub> for the classification of sands, it may be worthwhile to use this parameter to classify these sand samples into mafic, intermediate, and felsic compositions (Figure 3). This kind of classification has been used by Hayashi *et al.* (1997).

All sand samples analyzed in this study generally have intermediate to felsic composition, mostly between 53 and 83% in (SiO<sub>2</sub>)<sub>adj</sub> content, except one mafic sample from Acapulco (Aca-2, 48.8%; Figure 3). The (SiO<sub>2</sub>)<sub>adj</sub> content for Cazonés sands are also quite variable from  $\sim 54\%$  to 83%. Among these samples, three sands (Caz-7, Caz-5, Caz-2) are intermediate in composition (Table 4). Similarly, there is a wide scatter in (SiO<sub>2</sub>)<sub>adj</sub> content for the Acapulco sands ranging from  $\sim 49$  to 80%. However, except two samples (Aca-2, Aca-6), others are felsic in composition (Figure 3; Table 4). On the other hand, the variations in (SiO<sub>2</sub>)<sub>adj</sub> content among Bahía Kino sands are much less ( $\sim 73$  to 81%); these samples are felsic in composition (Figure 3), except sample Bah-3 (62.4%).

The variation in Al<sub>2</sub>O<sub>3</sub>/TiO<sub>2</sub> ratio is larger for Acapulco sands ( $\sim 3$ – $198$ ; Table 4; Figure 3) than for Bahía Kino ( $\sim 53$ – $72$ ), and Cazonés sands ( $\sim 18$ – $36$ ). Similarly, Al<sub>2</sub>O<sub>3</sub> contents in Acapulco sands range from  $\sim 8\%$  to 16%; for comparison, in Bahía Kino sands they vary from  $\sim 8\%$  to 11% and in Cazonés sands from  $\sim 5\%$  to 9%. The TiO<sub>2</sub> concentration is also higher in the three Acapulco sands

Table 1. Evaluation of ICP-MS data quality by comparison of reference sample JG-2 data with the published literature.

Elements (ppm)	Reference JG2 analyzed as sample	Compilation of JG2 mean value (Imai <i>et al.</i> 1995)	Compilation JG-2 Guevara <i>et al.</i> (2001)	
			mean	95% CI*
Ba	67.331	67.00	69.00	65 – 74
Co	4.343	4.30	3.5	3.3 – 3.8
Cr	7.346	7.60	6.2	5.3 – 7.1
Cs	7.600	7.50	7.2	7.0 – 7.4
Cu	0.320	0.40	–	–
Ga	18.905	19.00	18.0	17.2 – 18.7
Hf	5.528	5.36	–	–
Nb	14.934	15.00	14.5	14.0 – 15.0
Ni	1.680	2.10	2.2	1.5 – 2.9
Pb	33.115	32.80	31.7	31.2 – 32.2
Rb	298.825	297.00	300.6	298.7 – 302.6
Sc	2.489	2.47	2.52	2.37 – 2.67
Sr	16.061	16.00	17.1	16.5 – 17.8
Th	30.363	29.70	31.8	30.6 – 33.0
U	12.739	12.50	11.2	10.7 – 11.8
V	2.924	3.00	3.7	2.8 – 4.7
Y	88.312	88.20	85	82 – 88
Zn	12.640	12.70	13.2	12.4 – 14.1
Zr	100.912	101.00	96	93 – 99
La	20.230	20.10	19.6	19.2 – 20.0
Ce	49.950	49.50	48.6	47.6 – 49.6
Pr	6.066	6.01	6.5	6.2 – 6.8
Nd	26.043	25.80	25.5	24.6 – 26.4
Sm	7.761	7.72	7.8	7.4 – 8.2
Eu	0.079	0.09	0.090	0.077 – 0.103
Gd	7.006	7.10	9.1	8.4 – 9.7
Tb	1.522	1.50	2.7	2.4 – 3.0
Dy	11.738	11.50	11.8	11.2 – 12.3
Ho	1.399	1.40	2.1	1.7 – 2.5
Er	4.970	4.95	7.4	6.9 – 8.0
Tm	0.721	0.70	1.12	1.06 – 1.19
Yb	7.569	7.34	8.1	7.7 – 8.4
Lu	1.228	1.22	1.21	1.18 – 1.25

\* Confidence interval.

(Aca-2, Aca-3, and Aca-6; Table 4) than all other sand samples, at 99% confidence level as determined from  $f$  and  $t$  tests (Verma, 2005).

It is generally considered that Al and Ti are not fractionated relative to each other during weathering, transportation and diagenesis (Garcia *et al.*, 1994). However, the measured correlation between  $\text{TiO}_2$  and  $\text{Al}_2\text{O}_3$  for all sand samples is statistically not significant ( $r = 0.14$ ,  $n = 24$ ; critical  $t$  value for 99% confidence level is 0.487; Verma, 2005), which may be partly due to the variation in  $\text{Al}_2\text{O}_3/\text{TiO}_2$  ratios among individual study areas (Sugitani *et al.*, 2006). Furthermore, the similar enrichment in  $\text{TiO}_2$ ,  $\text{Fe}_2\text{O}_3$ , and MgO contents (Table 4) in the three Acapulco sands (Aca-2, Aca-3, and Aca-6) probably reflect the abundance of Ti-bearing heavy minerals like ilmenite (Table 3).

Figure 4 shows the  $\text{K}_2\text{O}/\text{Na}_2\text{O}-\text{SiO}_2/\text{Al}_2\text{O}_3$  relationship for all sands as well as probable source rocks. The

average geochemical data used in this plot for comparison are from the source areas located relatively close to the study areas (see Figure 1 for more details). The mean values of  $\text{SiO}_2/\text{Al}_2\text{O}_3$  for felsic sands of all three areas (Cazones, Acapulco and Bahía Kino) are slightly higher as compared to their respective source rocks (Figure 4).

### Trace element geochemistry

Trace element concentrations are reported in Table 5. The Bahía Kino sands are higher in Ba, Rb, Th, U, Zr, and Hf than Acapulco and Cazones sands. However, other trace elements like Co, Cr, Sc, and V are higher in Acapulco than in Cazones and Bahía Kino sands. Two samples from Cazones (Caz-1 and Caz-3) and four from Bahía Kino (Bah-2, Bah-4, Bah-5, and Bah-7) are higher in Zr and Hf.

Table 2. Graphic mean size, sorting parameters and petrography for the beach sands of Mexico, expressed in %.

Sample	M <sub>Z</sub>	σ	Qt	Ft	LF
<i>Cazones</i>					
Caz-1	1.97	0.53	45	12	43
Caz-2	3.42	0.51	31	23	46
Caz-3	1.42	0.71	35	20	45
Caz-4	3.83	0.63	46	10	44
Caz-5	1.76	0.66	22	25	53
Caz-6	3.80	0.68	48	22	30
Caz-7	1.61	0.54	32	25	43
Caz-8	3.52	0.49	41	17	42
Mean	2.7 ± 1.1	0.60 ± 0.09	38 ± 9	19 ± 6	43 ± 6
<i>Acapulco</i>					
Aca-1	1.70	1.10	48	19	33
Aca-2	3.90	1.02	20	14	66
Aca-3	0.91	1.07	43	16	41
Aca-4	1.21	1.08	47	19	34
Aca-5	1.68	1.32	44	25	31
Aca-6	1.56	0.99	25	12	63
Aca-7	0.84	1.07	38	24	38
Aca-8	2.12	1.16	30	20	50
Mean	1.7 ± 0.97	1.1 ± 0.1	36 ± 11	19 ± 4	45 ± 14
<i>Bahia Kino</i>					
Bah-1	0.86	0.50	53	32	15
Bah-2	1.98	0.38	65	25	10
Bah-3	1.00	0.48	48	26	26
Bah-4	1.71	0.45	75	18	7
Bah-5	0.49	0.38	83	9	8
Bah-6	1.58	0.49	78	12	10
Bah-7	0.42	0.50	54	28	18
Bah-8	1.65	0.39	52	30	18
Mean	1.2 ± 0.6	0.45 ± 0.05	63 ± 14	23 ± 9	14 ± 6

M<sub>Z</sub>: grain size (in φ units); σ: sorting (in φ units); Qt: total quartz (mono- and polycrystalline quartz); Ft: total feldspar (plagioclase + feldspar); LF: rock fragments (sedimentary + metamorphic + volcanic + plutonic).

The differences in trace element contents among the three study areas are probably due to the sorting effect of sands or differences in source rocks.

### Rare-earth element geochemistry

The results of REE analysis for Cazones, Acapulco, and Bahía Kino sands are presented in Table 6. The ΣREE contents are higher in Acapulco sands (~22–390 ppm) than in Cazones (~49–83 ppm) and Bahía Kino sands (~50–89 ppm) at 99% confidence level as determined from *F* and *t* tests. However, for felsic sands the ΣREE contents of Bahía Kino are slightly higher than in Cazones and Acapulco sands (Table 6). On the other hand, the ΣREE contents in three intermediate Cazones sands (Caz-7, Caz-5, and Caz-2) are higher than in felsic sands (Table 6). Similarly, an intermediate sand from Acapulco (Aca-6) has the highest ΣREE content. A larger variation in HREE content is observed in

Acapulco sands (~3–47 ppm) than in Cazones (~5–9 ppm) and in Bahía Kino sands (~5–8 ppm), and is likely due to the result of the differences in fractionation of minerals (Lee, 2009). Among felsic sands, the LREE and HREE contents are slightly higher in Bahía Kino sands than in Cazones and Acapulco sands (Table 6).

All the sand samples show similar REE patterns (Figure 5a, b, c), with enriched LREE ( $La_{cn}/Sm_{cn} = 4.0 \pm 0.70$ ;  $n = 24$ ), depleted HREE ( $Gd_{cn}/Yb_{cn} = 1.35 \pm 0.14$ ) and a negative Eu anomaly ( $Eu/Eu^* = 0.76 \pm 0.14$ ). Considering the individual study areas, the variations in Eu anomalies are higher in Acapulco sands (~0.46–1.13) than in Cazones (~0.69–0.90) and Bahía Kino sands (~0.66–0.80). However, the variations in average  $Eu/Eu^*$  ratio within felsic sands for the three study areas are less. In addition, small positive Eu anomaly is identified in the felsic sand Aca-7 ( $Eu/Eu^* = 1.13$ ).

## DISCUSSION

### Weathering conditions

The degree of alteration of feldspars to clays indicates both the degree of weathering of the source rocks and that of the diagenesis experienced by the sediments since deposition (Nesbitt *et al.*, 1997; Selvaraj and Chen, 2006). Various weathering indexes have been developed and are extensively used (*e.g.*, Price and Velbel, 2003; Armstrong-Altrin *et al.*, 2004; Borges and Huh, 2007; Varga *et al.*, 2007; Nagarajan *et al.*, 2007a, 2007b; Pe-Piper *et al.*, 2008; Viers *et al.*, 2008; Lee, 2009) to identify the chemical weathering intensity of source area. Some examples are *weathering index of Parker* (WIP; Parker, 1970), *chemical index of weathering* (CIW; Harnois, 1988), *chemical index of alteration* (CIA; Nesbitt and Young, 1982) and *Plagioclase index of alteration* (PIA; Fedo *et al.*, 1995). Among these weathering indices, a chemical index widely used to determine the degree of source area weathering is the chemical index of alteration (Nesbitt and Young, 1982). This can be calculated using the formula (molecular proportions)  $CIA = [Al_2O_3 / (Al_2O_3 + CaO^* + Na_2O + K_2O)] \times 100$ , where  $CaO^*$  is the amount of

Table 3. Major heavy mineral distributions for the beach sands of Mexico.

	Heavy minerals					
	zircon	magnetite	ilmenite	titanomagnetite	monazite	garnet
<i>Cazones</i>						
a	s	s	n.d	n.d	n.d	
<i>Acapulco</i>						
s	a	v.a	a	n.d	s	
<i>Bahia Kino</i>						
v.a	n.d	n.d	scarce	n.d	n.d	

v.a: very abundant (40–50 %); a: abundant (20–40 %); s: scarce (10–20 %); n.d: not identified.

Table 4. Major element concentrations in weight % for the beach sands of Mexico.

Oxides	Samples - Cazones								Statistical parameters					
	Caz-7	Caz-5	Caz-2	Caz-3	Caz-4	Caz-8	Caz-6	Caz-1	Felsic sands			All sand samples		
	Intermediate			Felsic					<i>n</i>	<i>m</i>	<i>s</i>	<i>n</i>	<i>m</i>	<i>s</i>
SiO <sub>2</sub>	47.50	47.61	53.80	62.11	76.44	77.30	77.36	81.40	5	78.11	2.22	8	65.43	14.37
TiO <sub>2</sub>	0.17	0.16	0.22	0.16	0.29	0.34	0.17	0.27	5	0.25	0.08	8	0.22	0.07
Al <sub>2</sub> O <sub>3</sub>	5.02	5.23	4.86	5.01	8.59	6.24	6.17	8.33	5	6.87	1.54	8	6.20	1.50
Fe <sub>2</sub> O <sub>3</sub> *	20.62	19.70	19.60	0.99	0.82	1.07	0.70	0.69	5	0.85	0.17	8	8.02	9.89
MnO	0.53	0.53	0.53	0.02	0.01	0.01	0.01	0.01	5	0.01	0.00	8	0.21	0.27
MgO	0.40	0.38	0.38	0.15	0.45	0.24	0.20	0.45	5	0.30	0.14	8	0.33	0.12
CaO	10.46	10.27	7.67	16.05	5.67	6.07	5.96	5.28	5	5.74	0.35	8	8.43	3.70
Na <sub>2</sub> O	1.52	1.29	1.31	0.95	1.37	1.23	1.45	0.81	5	1.16	0.27	8	1.24	0.24
K <sub>2</sub> O	1.02	1.18	1.10	1.24	1.48	1.67	1.69	1.04	5	1.42	0.28	8	1.30	0.27
P <sub>2</sub> O <sub>5</sub>	0.15	0.14	0.13	0.06	0.04	0.40	0.03	0.03	5	0.03	0.006	8	0.08	0.05
LOI	13.34	13.04	10.64	13.58	6.44	6.41	6.86	1.11	5	6.51	0.25	8	8.93	4.45
Total	100.70	99.50	100.20	100.32	101.60	100.59	100.60	99.40	5	100.50	0.79	8	100	0.70
CaO*	0.98	2.10	0.98	1.25	2.01	1.42	1.23	2.12	5	1.61	0.43	8	1.51	0.50
CIA	48.24	42.02	48.66	49.18	53.35	49.78	48.89	56.90	5	51.53	3.52	8	49.57	4.28
(SiO <sub>2</sub> ) <sub>adj</sub>	54.34	55.07	60.07	71.60	80.33	82.05	82.53	82.80	5	79.86	4.71	8	71.10	12.72
Al <sub>2</sub> O <sub>3</sub> /TiO <sub>2</sub>	29.53	32.69	22.09	31.31	29.62	18.35	36.29	30.85	5	29.29	6.62	8	28.84	5.82
K <sub>2</sub> O/Na <sub>2</sub> O	0.67	0.92	0.84	1.31	1.08	1.36	1.17	1.28	5	1.24	0.11	8	1.08	0.25
SiO <sub>2</sub> /Al <sub>2</sub> O <sub>3</sub>	9.46	9.10	11.07	12.40	8.90	12.38	12.54	9.77	5	11.20	1.73	8	10.70	1.58

Oxides	Samples - Acapulco								Statistical parameters					
	Aca-2	Aca-6	Aca-3	Aca-4	Aca-7	Aca-1	Aca-8	Aca-5	Felsic sands			All sand samples		
	Mafic	Inter.	Felsic					<i>n</i>	<i>m</i>	<i>s</i>	<i>n</i>	<i>m</i>	<i>s</i>	
SiO <sub>2</sub>	48.20	53.00	63.88	66.80	69.47	73.36	73.43	78.43	6	70.90	5.24	8	65.82	10.47
TiO <sub>2</sub>	1.48	3.63	2.19	0.31	0.16	0.45	0.08	0.23	6	0.25	0.14	8	1.07	1.28
Al <sub>2</sub> O <sub>3</sub>	8.23	10.76	11.22	12.36	11.17	11.81	15.86	9.60	6	12.00	2.10	8	11.57	2.23
Fe <sub>2</sub> O <sub>3</sub> *	28.99	16.60	10.41	2.08	5.82	3.28	0.40	1.84	6	3.97	3.64	8	8.68	9.82
MnO	0.62	0.33	0.18	0.02	0.00	0.03	0.00	0.02	6	0.01	0.01	8	0.15	0.22
MgO	4.13	4.48	2.28	1.00	0.60	1.58	0.31	0.80	6	1.10	0.72	8	1.90	1.61
CaO	4.11	8.52	5.30	7.16	4.82	2.85	1.17	2.66	6	3.99	2.17	8	4.57	2.43
Na <sub>2</sub> O	1.98	1.47	2.02	2.68	2.46	3.04	3.19	2.30	6	2.62	0.45	8	2.39	0.57
K <sub>2</sub> O	0.71	0.86	1.39	2.33	4.96	1.72	4.41	1.92	6	2.79	1.51	8	2.29	1.58
P <sub>2</sub> O <sub>5</sub>	0.22	0.23	0.17	0.08	0.02	0.11	0.02	0.06	6	0.08	0.06	8	0.11	0.08
LOI	2.99	1.86	1.60	5.22	1.42	2.28	1.47	2.16	6	1.79	0.40	8	2.38	1.26
Total	101.66	101.74	100.64	100.04	100.90	100.51	100.34	100.02	6	100.41	0.35	8	101.00	0.67
CaO*	-	2.78	1.92	1.10	-	-	-	-	-	-	-	-	-	-
CIA	41.72	56.15	57.43	58.05	38.06	49.51	56.63	47.30	6	51.16	7.82	8	50.60	7.72
(SiO <sub>2</sub> ) <sub>adj</sub>	48.85	53.06	64.50	70.45	69.83	74.68	74.27	80.15	6	72.31	5.32	8	66.97	10.92
Al <sub>2</sub> O <sub>3</sub> /TiO <sub>2</sub>	5.56	2.96	5.12	39.87	69.81	26.24	198.25	41.74	6	63.51	69.32	8	27.33	24.94
K <sub>2</sub> O/Na <sub>2</sub> O	0.36	0.59	0.69	0.87	2.02	0.57	1.38	0.84	6	1.06	0.55	8	0.91	0.54
SiO <sub>2</sub> /Al <sub>2</sub> O <sub>3</sub>	5.86	4.93	5.69	5.40	6.22	6.21	4.63	8.17	6	6.05	1.19	8	5.89	1.08

Oxides	Samples - BahíaKino								Statistical parameters					
	Bah-3	Bah-8	Bah-7	Bah-1	Bah-5	Bah-6	Bah-2	Bah-4	Felsic sands			All sand samples		
	Inter.			Felsic					<i>n</i>	<i>m</i>	<i>s</i>	<i>n</i>	<i>m</i>	<i>s</i>
SiO <sub>2</sub>	61.33	72.32	73.99	77.17	78.88	79.57	79.87	79.93	7	77.39	3.08	8	75.38	6.35
TiO <sub>2</sub>	0.14	0.14	0.18	0.17	0.16	0.15	0.18	0.14	7	0.16	0.02	8	0.16	0.02
Al <sub>2</sub> O <sub>3</sub>	7.47	9.52	10.23	9.52	9.89	10.45	10.14	10.01	7	9.97	0.35	8	9.97	0.35
Fe <sub>2</sub> O <sub>3</sub> *	21.60	7.80	1.06	1.04	0.93	0.88	1.02	0.83	7	0.96	0.09	8	0.96	0.09
MnO	0.52	0.00	0.01	0.01	0.01	0.00	0.01	0.00	7	0.006	0.005	8	0.006	0.005
MgO	0.46	0.30	0.41	0.31	0.32	0.32	0.33	0.29	7	0.32	0.01	8	0.34	0.06
CaO	1.51	2.86	3.17	2.15	1.32	0.82	1.10	0.83	7	1.75	0.98	8	1.72	0.91
Na <sub>2</sub> O	2.16	2.50	3.06	2.58	2.28	2.30	2.33	2.28	7	2.48	0.28	8	2.44	0.29
K <sub>2</sub> O	2.91	4.09	4.24	4.23	4.04	4.03	3.85	4.01	7	4.07	0.13	8	4.07	0.14
P <sub>2</sub> O <sub>5</sub>	0.14	0.05	0.08	0.07	0.06	0.06	0.06	0.05	7	0.06	0.01	8	0.06	0.01
LOI	3.13	1.36	4.53	3.38	1.98	1.26	1.35	1.29	7	2.16	1.29	8	2.29	1.24
Total	101.37	100.94	100.96	100.63	99.87	99.84	100.24	99.66	7	100.31	0.54	8	100.00	0.63
CIA	44.15	40.93	39.94	42.78	48.44	52.03	50.35	51.04	7	46.50	5.13	8	46.21	4.82
(SiO <sub>2</sub> ) <sub>adj</sub>	62.43	72.63	76.73	79.35	80.58	80.72	80.77	81.25	7	78.86	3.15	8	76.81	6.50
Al <sub>2</sub> O <sub>3</sub> /TiO <sub>2</sub>	53.36	68.00	56.83	56.00	61.81	69.67	56.33	71.50	7	62.88	6.76	8	61.69	7.11
K <sub>2</sub> O/Na <sub>2</sub> O	1.35	1.64	1.39	1.64	1.77	1.75	1.65	1.76	7	1.66	0.13	8	1.62	0.17
SiO <sub>2</sub> /Al <sub>2</sub> O <sub>3</sub>	8.21	7.60	7.23	8.11	7.98	7.61	7.90	7.99	7	7.77	0.30	8	7.82	0.32

*n*: number of samples; *m*: mean; *s*: standard deviation; Fe<sub>2</sub>O<sub>3</sub>\*: Total Fe expressed as Fe<sub>2</sub>O<sub>3</sub>; Inter.: Intermediate; CaO\*: CaO in silicate phase and is calculated for the samples, which are greater than 5% in CaO content.



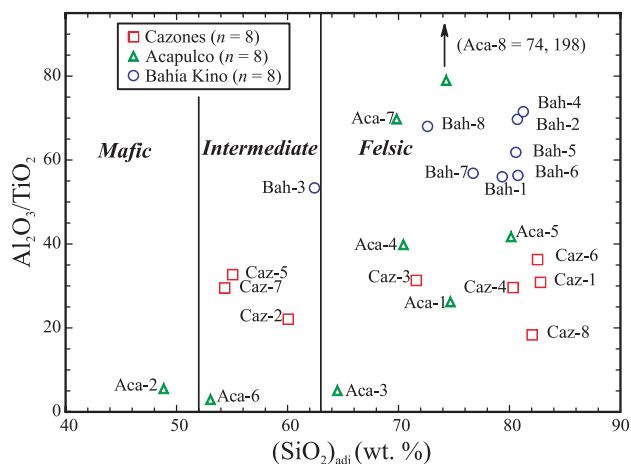


Figure 3. The  $\text{Al}_2\text{O}_3/\text{TiO}_2$  vs.  $\text{SiO}_2$  relationship for the beach sands. The fields based on  $(\text{SiO}_2)_{\text{adj}}$  are from Le Bas *et al.* (1986).  $n$ : number of samples.

CaO incorporated in the silicate fraction of the rock.

The calculated CIA values are presented in Table 4. The average CIA value is lower in Bahía Kino sands ( $46 \pm 5$ ,  $\sim 40\text{--}52$ ,  $n = 8$ ) than in Acapulco ( $\sim 51 \pm 8$ ,  $\sim 38\text{--}58$ ) and Cazones sands ( $50 \pm 4$ ,  $\sim 42\text{--}57$ ). However, the differences in average CIA values for the three study areas

are not statistically significant at 99% confidence level as determined from  $f$  and  $t$  tests (Verma, 2005). These values indicate a low intensity of chemical weathering in the source area. The differences in CIA values within felsic sands are smaller (Table 4).

The CIA values of all sand samples are plotted in  $\text{Al}_2\text{O}_3\text{--}(\text{CaO}^* + \text{Na}_2\text{O})\text{--}\text{K}_2\text{O}$  (A-CN-K) compositional space (molecular proportions) in Figure 6a, b, c, for Cazones, Acapulco, and Bahía Kino sands, respectively. The degree of weathering is quite variable for Cazones and Acapulco sands, which are scattered near the feldspar join line (Figure 6a, b). This scatter reveals steady state weathering conditions, which occur where climate and tectonism vary greatly, altering the rates of chemical weathering and erosion, and resulting in the production of chemically diverse sediments (Nesbitt *et al.*, 1997; Selvaraj and Chen, 2006). The Bahía Kino sands plot parallel to the A-CN line (Figure 6c) and define a non-steady state weathering trend towards the “A” join. This non-steady state weathering indicates balanced rates of chemical weathering and erosion, which produces compositionally similar sediments over a long period (Nesbitt *et al.*, 1997; Selvaraj and Chen, 2006). For comparison, the average geochemical data are also used in these plots, which are from the source areas located relatively close to the study areas (see Figure 1 for more details).

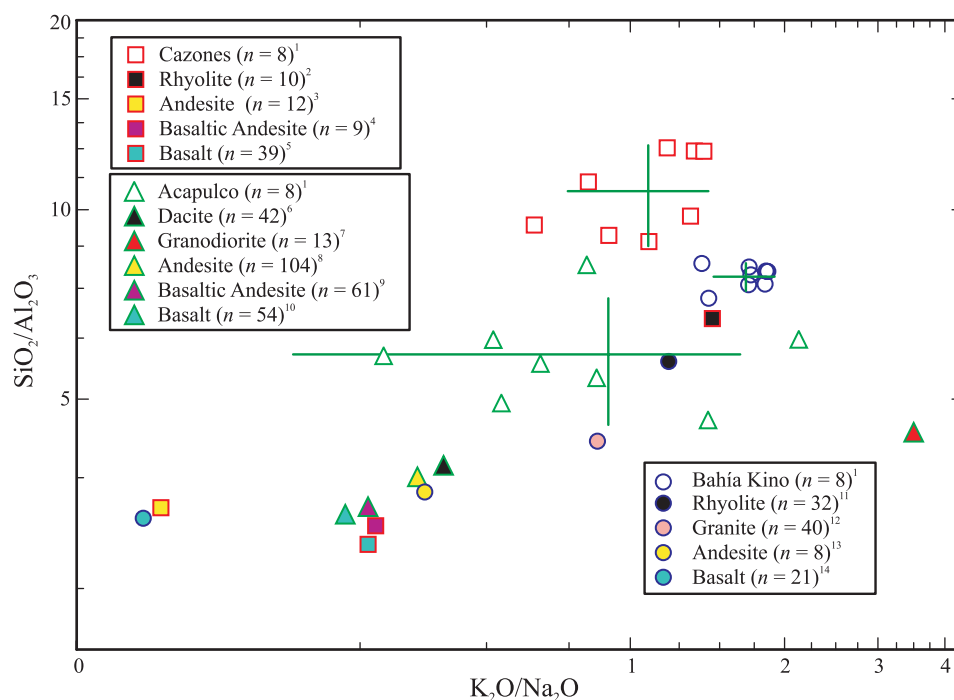


Figure 4.  $\text{K}_2\text{O}/\text{Na}_2\text{O}\text{--}\text{SiO}_2/\text{Al}_2\text{O}_3$  bivariate plot for the beach sands.  $n$  = number of samples; <sup>1</sup>This study; Average data for comparison are from <sup>2</sup> Verma (2001a, 2001b); <sup>3</sup> Rosales-Lagarde *et al.* (2005); <sup>4</sup> Verma (2001a, 2001b); <sup>5</sup> Verma (2000a, 2001a, 2001b), Gómez-Tuena *et al.* (2003), Carrasco-Núñez *et al.* (2005); <sup>6</sup> Schaff *et al.* (2005), Martínez-Serrano *et al.* (2004), Verma (1999), Márquez and Ignacio (2002), Wallace and Carmichael (1999); <sup>7</sup> Meza-Figueroa *et al.* (2003); <sup>8</sup> Schaff *et al.* (2005), Martínez-Serrano *et al.* (2004), Siebe *et al.* (2004), Verma (1999), Márquez and Ignacio (2002), Wallace and Carmichael (1999); <sup>9</sup> Schaff *et al.* (2005), Martínez-Serrano *et al.* (2004), Siebe *et al.* (2004), Velasco-Tapia and Verma (2001a), Verma (1999), Márquez and Ignacio (2002), Wallace and Carmichael (1999); <sup>10</sup> Schaff *et al.* (2005), Siebe *et al.* (2004), Verma (2000b), Velasco-Tapia and Verma (2001a), Márquez and Ignacio (2002), Wallace and Carmichael (1999); <sup>11</sup> Desonie (1992), Vidal-Solano *et al.* (2007); <sup>12</sup> Valencia-Moreno *et al.* (2001, 2003); <sup>13</sup> Desonie (1992); <sup>14</sup> Saunders *et al.* (1982), Saunders (1983).

Table 5. Trace element concentrations in ppm for the beach sands of Mexico.

	Samples - Cazones								Statistical parameters					
	Caz-7	Caz-5	Caz-2	Caz-3	Caz-4	Caz-8	Caz-6	Caz-1	Felsic sands			All sand samples		
	Intermediate				Felsic				<i>n</i>	<i>m</i>	<i>s</i>	<i>n</i>	<i>m</i>	<i>s</i>
Ba	499	545	526	518	520	567	570	364	5	507.91	84.01	8	535.09	26.53
Co	5.65	4.83	4.19	4.69	3.44	4.24	3.35	3.06	5	3.76	0.68	8	4.20	0.87
Cr	7.40	7.37	8.12	7.54	5.96	11.78	6.85	8.77	5	8.18	2.26	8	7.97	1.74
Cs	1.91	1.89	1.51	8.07	1.46	1.84	1.92	6.80	5	4.02	3.16	8	3.17	2.66
Cu	0.67	0.56	0.77	0.65	0.76	0.95	0.63	0.66	5	0.73	0.13	8	0.71	0.12
Ga	8.45	8.25	7.42	18.62	7.15	8.37	8.22	15.25	5	11.52	5.10	8	10.22	4.27
Hf	2.65	2.05	2.02	30.13	1.87	2.76	2.59	26.71	5	12.81	14.31	8	8.85	12.12
Nb	6.44	5.06	5.86	4.05	6.60	8.16	4.74	6.17	5	5.94	1.61	8	5.88	1.28
Ni	3.13	2.87	3.48	3.25	2.93	4.55	2.32	2.74	5	3.16	0.85	8	3.12	0.66
Pb	45.08	42.63	37.29	42.63	38.22	42.27	44.03	48.01	5	43.03	3.52	8	45.52	3.48
Rb	54.65	60.04	54.26	50.13	55.41	64.61	63.03	34.07	5	53.45	12.31	8	54.52	9.58
Sc	3.54	3.01	2.88	2.87	2.66	2.66	2.30	2.19	5	2.54	0.28	8	2.76	0.42
Sr	360	334	286	404	207	222	218	141	5	197.07	38.09	8	271.59	89.57
Th	4.43	4.00	3.30	3.70	3.20	3.80	3.40	2.80	5	3.36	0.40	8	3.55	0.51
U	1.98	1.70	1.43	2.34	1.42	1.47	1.33	1.74	5	1.66	0.41	8	1.68	0.34
V	13.23	11.05	10.65	12.64	9.34	10.94	7.05	9.66	5	9.93	2.07	8	10.57	1.94
Y	18.63	16.24	13.79	17.43	10.91	12.32	11.33	9.26	5	12.25	3.10	8	13.74	3.38
Zn	26.93	27.35	18.57	31.43	18.76	18.43	16.32	20.85	5	21.15	5.96	8	22.34	5.47
Zr	93.82	69.23	66.44	898	61.19	97.57	83.05	818	5	391.39	426.69	8	273.30	361.47
Th/U	2.23	2.33	2.29	1.56	2.23	2.57	2.53	1.61	5	2.10	0.49	8	2.17	0.38
Zr/Sc	26.57	23.02	23.06	312.3	23.02	36.75	36.09	373.32	5	156.30	171.71	8	106.76	146.71

	Samples - Acapulco								Statistical parameters					
	Aca-2	Aca-6	Aca-3	Aca-4	Aca-7	Aca-1	Aca-8	Aca-5	Felsic sands			All sand samples		
	Mafic	Inter.	Felsic						<i>n</i>	<i>m</i>	<i>s</i>	<i>n</i>	<i>m</i>	<i>s</i>
Ba	314	302	401	617	592	497	474	639	6	536.46	93.74	8	479.33	132.19
Co	30.82	30.24	16.88	5.46	1.25	10.52	1.44	4.95	6	6.75	6.00	8	12.69	12.12
Cr	32.68	20.30	15.31	11.17	6.29	17.08	4.62	7.88	6	10.39	5.02	8	14.42	9.19
Cs	2.55	1.19	2.77	3.37	2.41	3.66	2.21	1.63	6	2.67	0.75	8	2.47	0.82
Cu	0.93	0.76	0.87	0.54	0.50	0.76	0.39	0.64	6	0.62	0.18	8	0.67	0.19
Ga	17.38	24.77	20.15	11.50	15.58	15.37	17.01	10.99	6	15.10	3.44	8	16.59	4.47
Hf	4.34	5.12	3.89	1.55	1.63	8.52	0.81	1.09	6	2.92	2.95	8	3.37	2.64
Nb	17.10	41.81	24.81	4.01	2.39	5.39	2.92	3.15	6	3.57	1.17	8	12.70	14.32
Ni	9.03	3.98	3.78	2.64	2.33	3.93	1.97	4.13	6	3.13	0.92	8	3.25	0.90
Pb	46.25	50.71	43.13	48.89	42.95	41.69	42.35	39.95	6	43.16	3.04	8	44.49	3.79
Rb	37.82	29.48	58.10	92.74	185.81	66.99	172.65	67.35	6	107.27	57.07	8	88.87	59.10
Sc	17.04	31.97	19.00	5.13	1.67	6.51	1.85	4.68	6	3.97	2.13	8	10.98	10.73
Sr	315	396	313	563	99.03	313	138	255	6	279.96	164.80	8	298.89	145.26
Th	9.42	21.50	14.50	3.73	2.25	4.30	2.50	3.22	6	3.19	0.85	8	7.67	7.00
U	3.22	6.37	4.56	1.54	0.97	2.02	1.00	1.15	6	1.33	0.44	8	2.60	1.97
V	93.27	139.94	85.67	15.69	5.42	23.62	4.23	13.61	6	12.51	7.96	8	47.68	51.37
Y	32.79	89.49	50.49	13.62	5.55	16.83	7.54	10.68	6	10.84	4.54	8	28.37	28.94
Zn	53.23	53.95	39.16	20.75	25.12	40.99	13.67	23.82	6	27.25	10.71	8	33.83	15.19
Zr	127	103	97.68	44.31	49.20	320	16.05	29.43	6	47.33	31.01	8	66.64	42.13
Th/U	2.93	3.37	3.18	2.43	2.32	2.13	2.50	2.81	6	2.56	0.38	8	2.71	0.44
Zr/Sc	7.44	3.22	5.14	8.63	29.46	49.12	8.69	6.29	6	17.89	17.76	8	14.75	16.13

This comparison reveals that the studied sand samples are weakly affected by chemical weathering.

### Mineral fractionation

Hydraulic sorting of detrital mineral grains can significantly influence the chemical composition of bulk sediments and control the distribution of some trace elements (e.g., REE, Th, U, Zr, Hf, Nb). Therefore, these conservative elements may not be representative of provenance if heavy mineral concentrations affect the elemental distribution

(e.g., Morton and Hallsworth, 1999; Hughes *et al.*, 2000; Campos-Alvarez and Roser, 2007; Ohta, 2008). It is also widely accepted that mineral fractionation can lead to variation in  $\Sigma$ REE concentrations in terrigenous sediments with different grain-size fractions and heavy mineral contents (Armstrong-Altrin *et al.*, 2004; López *et al.*, 2005; Caja *et al.*, 2007; Kasper-Zubillaga *et al.*, 2008b; Fanti, 2009).

The wide variation in  $\Sigma$ REE within the Acapulco sands (~22–390 ppm) are chiefly due to the higher concentration of  $\Sigma$ REE in three samples (Aca-2, Aca-6, and Aca-3) of the Acapulco sands, which are classified as mafic, intermediate, and felsic, respectively (Figure 3). It is identified that the

Table 5 (Continued). Trace element concentrations in ppm for the beach sands of Mexico.

	Samples – Bahía Kino								Statistical parameters					
	Bah-3	Bah-8	Bah-7	Bah-1	Bah-5	Bah-6	Bah-2	Bah-4	Felsic sands			All sand samples		
	Inter.	Felsic							<i>n</i>	<i>m</i>	<i>s</i>	<i>n</i>	<i>m</i>	<i>s</i>
Ba	1064	1122	1093	1110	1113	497	1104	1110	7	1109	9.64	8	1102	19.03
Co	2.97	2.85	3.41	2.98	3.19	0.83	3.21	2.87	7	3.08	0.22	8	3.07	0.21
Cr	7.83	7.17	6.17	7.35	6.54	4.71	5.46	6.51	7	6.27	0.93	8	6.47	1.02
Cs	4.74	5.09	10.30	4.83	12.35	1.17	10.40	6.08	7	7.17	3.96	8	6.87	3.77
Cu	0.52	0.59	0.59	0.72	0.64	0.25	0.47	0.48	7	0.53	0.15	8	0.53	0.14
Ga	11.44	12.38	21.58	11.41	25.39	2.06	22.13	15.37	7	15.76	8.01	8	15.22	7.58
Hf	2.60	2.05	25.31	2.71	36.34	0.71	26.99	27.73	7	17.40	15.00	8	15.56	14.84
Nb	7.20	5.09	8.19	6.55	7.39	1.41	6.71	5.63	7	5.85	2.21	8	6.02	2.10
Ni	2.46	2.74	2.48	3.30	3.76	1.87	2.55	2.56	7	2.76	0.61	8	2.72	0.57
Pb	44.02	47.94	47.04	48.13	48.98	33.92	51.44	46.68	7	48.37	1.71	8	47.75	2.27
Rb	178	184	184	183	181	34.51	175	108	7	150.00	57.88	8	153.53	54.51
Sc	2.38	2.31	2.62	2.33	2.61	1.39	2.49	2.49	7	2.47	0.13	8	2.46	0.19
Sr	216	193	280	226	208	52.93	191	187	7	214.00	35.89	8	214.28	32.31
Th	9.81	7.72	15.41	9.84	8.70	5.84	8.64	7.82	7	9.13	3.03	8	8.33	1.38
U	2.84	2.17	4.19	2.85	3.83	0.62	3.05	3.56	7	2.90	1.21	8	2.89	1.12
V	8.23	6.41	9.88	6.91	10.87	2.51	9.82	7.38	7	7.68	2.85	8	7.75	2.64
Y	14.21	11.44	14.85	13.58	13.20	9.32	12.78	12.81	7	12.57	1.76	8	12.78	1.73
Zn	16.45	18.85	20.24	18.79	25.31	9.87	24.05	22.72	7	19.97	5.12	8	19.53	4.90
Zr	75.00	60.44	784.00	80.22	142	18.68	801	89.00	7	567.91	499.90	8	506.27	494.6
Th/U	3.46	3.55	3.68	3.46	2.26	9.41	2.83	2.20	7	3.00	0.66	8	3.06	0.63
Zr/Sc	31.47	26.12	299.35	34.51	438.4	13.44	321.0	436.94	7	224.27	194.01	8	200.17	192.1

For abbreviations see foot note of Table 4.

enrichment of  $\Sigma$ REE are approximately four times higher in these three samples than in others (Table 6). Generally, the differences in  $\Sigma$ REE content among beach sands may occur as result of physical processes such as grain size, weathering, and/or addition of heavy minerals. However, the relationship between grain size (Mz; Table 2) and  $\Sigma$ REE are not significant (Table 6). In order to interpret the effect of weathering in the studied samples, the Th/U ratio is considered since weathering causes an elevation of Th/U ratio above upper crustal igneous values from 3.5 to 4.0 (McLennan *et al.*, 1993). The average Th/U ratio for the three study areas are less than  $\sim 4$  (Table 5), which reveals moderate weathering and are consistent with the CIA values (Table 4). Another possibility for the variations in  $\Sigma$ REE may be the addition of heavy minerals, and many studies showed that the addition of zircon, and/or ilmenite may cause the differences in the  $\Sigma$ REE content (*e.g.*, López *et al.*, 2005; Pe-Piper *et al.*, 2008). The petrography study reveals the presence of zircon grains in two felsic sands of Cazon (Caz-1, Caz-3) and in four felsic sands of Bahía Kino (Bah-2, Bah-4, Bah-5, and Bah-7), but not in the Acapulco sands. Also, these six felsic sands have higher Zr and Hf contents and Zr/Sc ratio at 99% confidence level as determined from *f* and *t* tests (Table 5); these elements are commonly used to identify the presence of zircon in sands (*e.g.*, Roddaz *et al.*, 2005, 2006). The concentration of zircon in these six felsic sands is also supported by the depletion in Cr/Zr ratio (Ishiga and Dozen, 1997). However, the average  $\Sigma$ REE concentration in these six felsic sands (Caz-1, Caz-3, Bah-2, Bah-4, Bah-5, and Bah-7) are lower ( $\sim 49$ – $89$  ppm; Table 6) than in the three Acapulco sands (Aca-2, Aca-3, and Aca-6) at 99% confidence level as determined from *f*

and *t* tests (Verma, 2005). This suggests that the enrichment of  $\Sigma$ REE content is not influenced by zircon.

Furthermore, concentration of Ti-bearing minerals like ilmenite during recycling would lead to an increase in TiO<sub>2</sub> abundances in the respective samples (García *et al.*, 1994, 2004; Mongelli *et al.*, 1996; Condie *et al.*, 2001; Campo and Guevara, 2005; Cai *et al.*, 2008; Pe-Piper *et al.*, 2008). In this study, the higher abundances of TiO<sub>2</sub>, Ta, Nb, and Nd contents, particularly in the three Acapulco sands (Aca-2, Aca-3, and Aca-6; Tables 4 and 5), are consistent with the observed presence of the Ti-bearing mineral ilmenite (Moore *et al.*, 1992; Das *et al.*, 2006; Bernstein *et al.*, 2008; Kasper-Zubillaga *et al.*, 2008a). Occurrence of ilmenite mineral along the southwestern Mexican Pacific coast was also documented by Carranza-Edwards *et al.* (2009). For the Acapulco sands, there is a statistically significant positive correlation between TiO<sub>2</sub> and  $\Sigma$ REE content ( $r = 0.9967$ ;  $n = 8$ ; critical *t* value for 99% confidence level is 0.834; Verma, 2005). Hence, it is interpreted that the higher  $\Sigma$ REE content in the three samples might be due to ilmenite, which probably is an indicator of the source rocks. Some ilmenite minerals from felsic igneous rocks show relatively high values of the partition coefficients, especially for LREE (Torres-Alvarado *et al.*, 2003). However, the presence of negative Eu anomaly in these three samples from Acapulco point to a more complex nature of the processes leading to the REE enrichment.

The above arguments suggest that special care should be taken when identifying provenance using geochemistry of beach sands (Marsaglia, 1992; Zhang *et al.*, 1998; Kasper-Zubillaga *et al.*, 1999), especially on Ti and Zr, which are largely influenced by the abundances of heavy

Table 6. Rare earth element concentrations in ppm for the beach sands of Mexico.

	Samples - Cazones								Statistical parameters					
	Caz-7	Caz-5	Caz-2	Caz-3	Caz-4	Caz-8	Caz-6	Caz-1	Felsic sands			All sand samples		
	Intermediate				Felsic				<i>n</i>	<i>m</i>	<i>s</i>	<i>n</i>	<i>m</i>	<i>s</i>
La	17.34	15.82	13.77	15.63	13.83	16.17	13.46	10.97	5	14.01	2.05	8	14.62	2.01
Ce	32.34	28.82	25.10	28.71	24.88	29.53	24.05	19.85	5	25.41	3.90	8	26.66	3.93
Pr	3.99	3.58	3.01	3.50	2.88	3.40	2.84	2.34	5	2.99	0.47	8	3.19	0.52
Nd	16.45	14.35	12.32	14.63	11.54	13.41	11.44	9.06	5	12.01	2.12	8	12.90	2.30
Sm	3.26	2.99	2.51	3.01	2.13	2.41	2.19	1.75	5	2.30	0.46	8	2.53	0.52
Eu	0.70	0.68	0.63	0.63	0.56	0.60	0.58	0.39	5	0.55	0.09	8	0.60	0.10
Gd	2.64	2.37	2.05	2.49	1.64	1.93	1.65	1.43	5	1.83	0.41	8	2.03	0.44
Tb	0.45	0.38	0.32	0.41	0.27	0.32	0.27	0.24	5	0.30	0.07	8	0.33	0.08
Dy	2.97	2.64	2.18	2.71	1.76	2.02	1.83	1.49	5	1.96	0.46	8	2.20	0.52
Ho	0.33	0.29	0.24	0.29	0.20	0.22	0.20	0.17	5	0.23	0.05	8	0.24	0.05
Er	1.09	0.97	0.82	1.02	0.69	0.75	0.71	0.56	5	0.75	0.17	8	0.83	0.18
Tm	0.15	0.12	0.11	0.13	0.09	0.10	0.09	0.08	5	0.10	0.02	8	0.11	0.02
Yb	1.46	1.23	1.06	1.34	0.89	1.04	0.91	0.82	5	1.00	0.21	8	1.09	0.23
Lu	0.23	0.20	0.18	0.22	0.16	0.17	0.15	0.14	5	0.17	0.03	8	0.18	0.03
ΣREE	83.38	74.44	64.29	74.72	61.51	72.07	60.37	49.29	5	63.59	10.18	8	67.51	10.70
LREE	73.37	65.56	56.70	65.47	55.26	64.92	53.97	43.98	5	56.72	8.89	8	59.90	9.18
HREE	9.31	8.20	6.96	8.61	5.70	6.55	5.82	4.92	5	6.32	1.40	8	7.01	1.56
Eu/Eu*	0.710	0.903	0.823	0.690	0.876	0.819	0.753	0.731	5	0.80	0.09	8	0.79	0.08
(Gd/Yb) <sub>cn</sub> †	1.46	1.57	1.57	1.50	1.50	1.50	1.46	1.41	5	1.48	0.04	8	1.50	0.05

	Samples - Acapulco								Statistical parameters					
	Aca-2	Aca-6	Aca-3	Aca-4	Aca-7	Aca-1	Aca-8	Aca-5	Felsic sands			All sand samples		
	Mafic	Inter.	Felsic						<i>n</i>	<i>m</i>	<i>s</i>	<i>n</i>	<i>m</i>	<i>s</i>
La	31.87	74.03	43.92	12.24	4.82	15.20	6.04	9.56	6	9.57	4.30	8	24.71	24.12
Ce	63.68	155.92	90.00	23.42	7.63	28.03	13.54	17.66	6	18.05	8.02	8	49.98	51.22
Pr	7.52	18.36	10.43	2.82	1.08	3.42	1.43	2.18	6	2.18	0.96	8	0.90	5.99
Nd	31.62	76.95	43.13	11.83	4.46	14.55	6.06	9.03	6	9.19	4.12	8	24.70	25.04
Sm	6.45	15.52	8.81	2.42	0.90	2.99	1.29	1.88	6	1.90	0.84	8	5.03	5.05
Eu	1.20	2.16	1.38	0.64	0.32	0.74	0.31	0.53	6	0.65	0.40	8	0.90	0.64
Gd	5.12	12.74	7.20	2.03	0.77	2.40	1.01	1.48	6	1.54	0.68	8	4.09	4.14
Tb	0.85	2.20	1.26	0.33	0.14	0.41	0.18	0.25	6	0.26	0.11	8	0.70	0.72
Dy	5.82	15.11	8.49	2.34	0.97	2.68	1.27	1.80	6	1.81	0.71	8	4.81	4.89
Ho	0.63	1.70	0.95	0.26	0.11	0.31	0.14	0.20	6	0.20	0.08	8	0.54	0.55
Er	2.06	5.80	3.18	0.84	0.35	1.03	0.50	0.67	6	0.08	0.27	8	1.80	1.87
Tm	0.28	0.77	0.41	0.11	0.05	0.14	0.07	0.09	6	0.09	0.04	8	0.24	0.24
Yb	2.75	7.91	4.36	1.14	0.52	1.41	0.76	0.92	6	0.95	0.34	8	2.47	2.54
Lu	0.46	1.30	0.68	0.18	0.09	0.25	0.13	0.15	6	0.16	0.06	8	0.40	0.41
ΣREE	160.30	390.44	224.22	60.60	22.19	73.57	32.73	46.39	6	47.10	20.68	8	126.31	127.38
LREE	141.13	340.78	196.30	52.73	18.92	64.20	28.35	40.31	6	40.89	18.20	8	110.33	111.40
HREE	17.97	47.51	26.54	7.23	2.99	8.63	4.07	5.56	6	5.70	2.29	8	15.06	15.36
Eu/Eu*	0.618	0.456	0.515	0.852	1.134	0.820	0.815	0.936	6	0.84	0.20	8	0.768	0.230
(Gd/Yb) <sub>cn</sub> †	1.51	1.31	1.34	1.45	1.20	1.38	1.07	1.30	6	1.29	0.13	8	1.32	0.14

minerals (Garcia *et al.*, 1994; Pe-Piper *et al.*, 2008). It is also observed that the zircon geochemistry did not affect the REE distribution and the patterns in the six felsic sands (Caz-1, Caz-3, Bah-2, Bah-4, Bah-5, and Bah-7) from Cazones and Bahía Kino. This is consistent with the study by Hoskin and Ireland (2000), which showed that zircon grains from different rock types have very similar chondrite-normalized REE patterns and abundances, and the zircon REE patterns and abundances are generally not useful as indicators of provenance (also see Poller *et al.*, 2001). Although the importance of alongshore transport processes on the provenance and composition of beach sand is observed along the coasts of several countries (*e.g.*, Pandarinath and Narayana, 1991; Narayana and Pandarinath, 1991; Narayana *et al.*, 1991; Hegde *et al.*,

2006; Kasper-Zubillaga *et al.*, 2007; Khalifa *et al.*, 2009), their influence in the provenance and composition of beach sands of the present work appears negligible.

## Provenance

In order to identify the provenance, the REE data of the source rocks, located relatively close to the study areas are compared to the present study (refer Figure 1, for locations and other details). The chondrite-normalized REE patterns for Cazones, Acapulco, and Bahía Kino sands together with the source rocks are given in the Figure 5a, b, and c, respectively.

The REE patterns observed for Cazones sands in

Table 6 (Continued). Rare earth element concentrations in ppm for the beach sands of Mexico.

	Samples - Bahía Kino								Statistical parameters					
	Bah-3	Bah-8	Bah-7	Bah-1	Bah-5	Bah-6	Bah-2	Bah-4	Felsic sands			All sand samples		
	Inter.	Felsic							<i>n</i>	<i>m</i>	<i>s</i>	<i>n</i>	<i>m</i>	<i>s</i>
La	20.22	16.80	20.21	20.42	18.17	13.04	18.72	17.00	7	17.77	2.51	8	18.07	2.50
Ce	35.83	29.53	38.22	35.78	32.01	17.20	33.50	29.98	7	30.89	6.78	8	31.51	6.52
Pr	4.02	3.31	4.08	3.97	3.61	2.62	3.79	3.38	7	3.54	0.50	8	3.60	0.49
Nd	15.37	12.65	15.51	14.88	13.86	10.00	14.25	12.77	7	13.42	1.83	8	13.66	1.83
Sm	2.61	2.22	2.73	2.72	2.40	1.83	2.48	2.32	7	2.39	0.31	8	2.41	0.30
Eu	0.55	0.53	0.57	0.53	0.53	0.39	0.55	0.52	7	0.54	0.02	8	0.54	0.02
Gd	2.00	1.72	2.19	2.01	1.94	1.35	1.91	1.80	7	1.85	0.27	8	1.87	0.25
Tb	0.32	0.26	0.36	0.31	0.30	0.21	0.30	0.28	7	0.29	0.04	8	0.29	0.04
Dy	2.13	1.82	2.33	2.18	2.04	1.46	1.96	1.91	7	1.96	0.28	8	1.98	0.26
Ho	0.25	0.21	0.26	0.26	0.24	0.17	0.24	0.24	7	0.23	0.03	8	0.23	0.03
Er	0.84	0.71	0.93	0.84	0.86	0.56	0.83	0.82	7	0.79	0.12	8	0.80	0.11
Tm	0.12	0.10	0.13	0.11	0.11	0.08	0.12	0.12	7	0.11	0.02	8	0.11	0.02
Yb	1.36	1.05	1.38	1.29	1.36	0.84	1.24	1.27	7	1.20	0.19	8	1.22	0.19
Lu	0.23	0.18	0.24	0.21	0.22	0.14	0.22	0.22	7	0.21	0.03	8	0.21	0.03
ΣREE	85.85	71.08	89.14	85.50	77.68	49.90	80.11	72.62	7	75.15	12.88	8	76.48	12.50
LREE	78.06	64.51	80.75	77.77	70.07	44.69	72.74	65.44	7	68.00	11.88	8	69.25	11.56
HREE	7.24	6.04	7.81	7.20	7.08	4.82	6.82	6.67	7	6.63	0.97	8	6.71	0.92
Eu/Eu*	0.710	0.799	0.696	0.660	0.729	0.728	0.743	0.744	7	0.73	0.04	8	0.659	0.799
(Gd/Yb) <sub>cn</sub> †	1.19	1.33	1.29	1.26	1.16	1.30	1.25	1.15	7	1.25	0.07	8	1.24	0.07

† Subscript <sub>cn</sub> refers to chondrite normalized values (Taylor and McLennan, 1985). For abbreviations see foot note of Table 4.

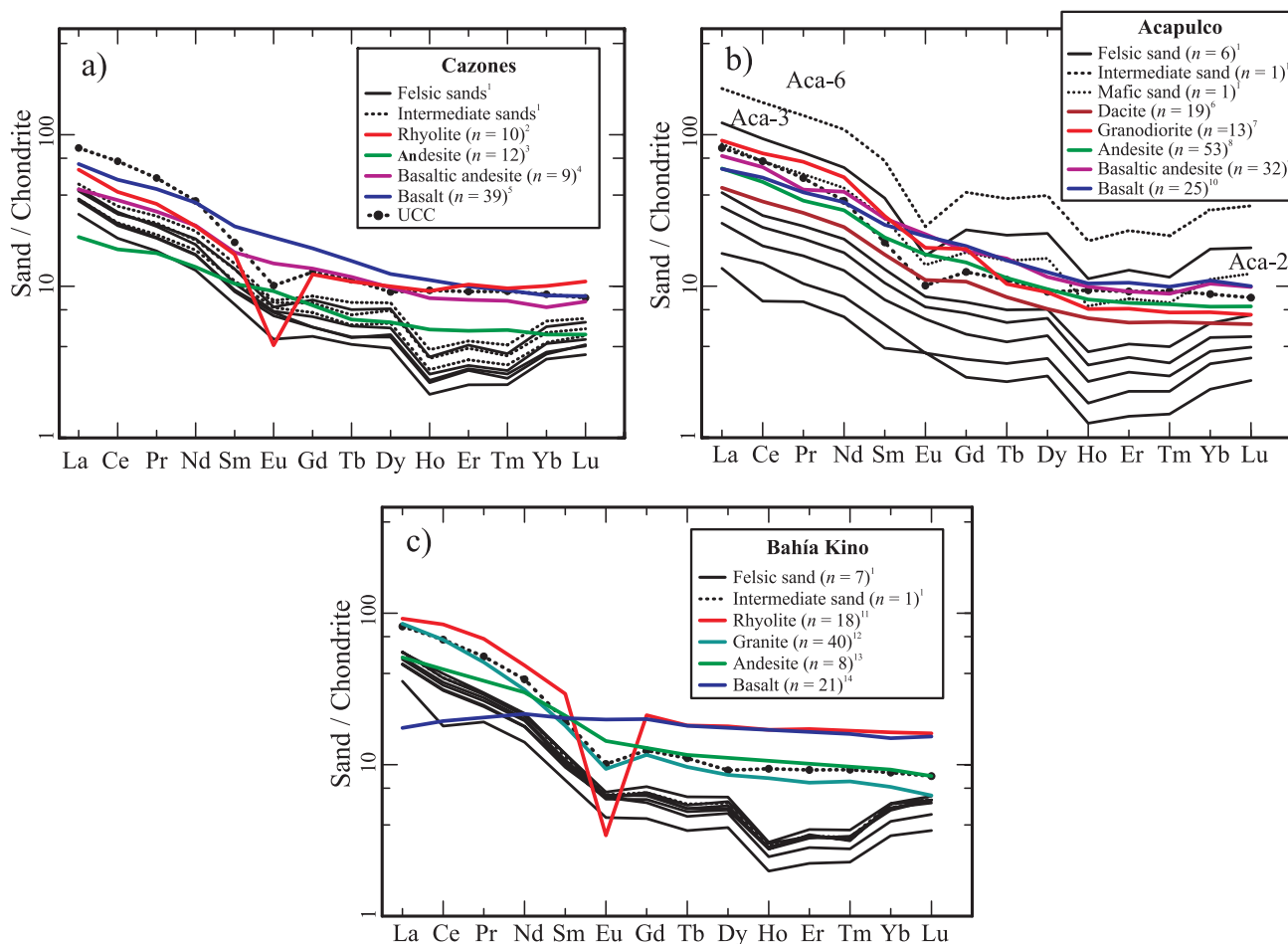


Figure 5. Chondrite-normalized REE patterns. a: Cazonces sands; b: Acapulco sands; c: Bahía Kino sands. <sup>1</sup> This study; *n*: number of samples; UCC: average upper continental crust (Taylor and McLennan, 1985). Refer to Figure 4 caption for references.

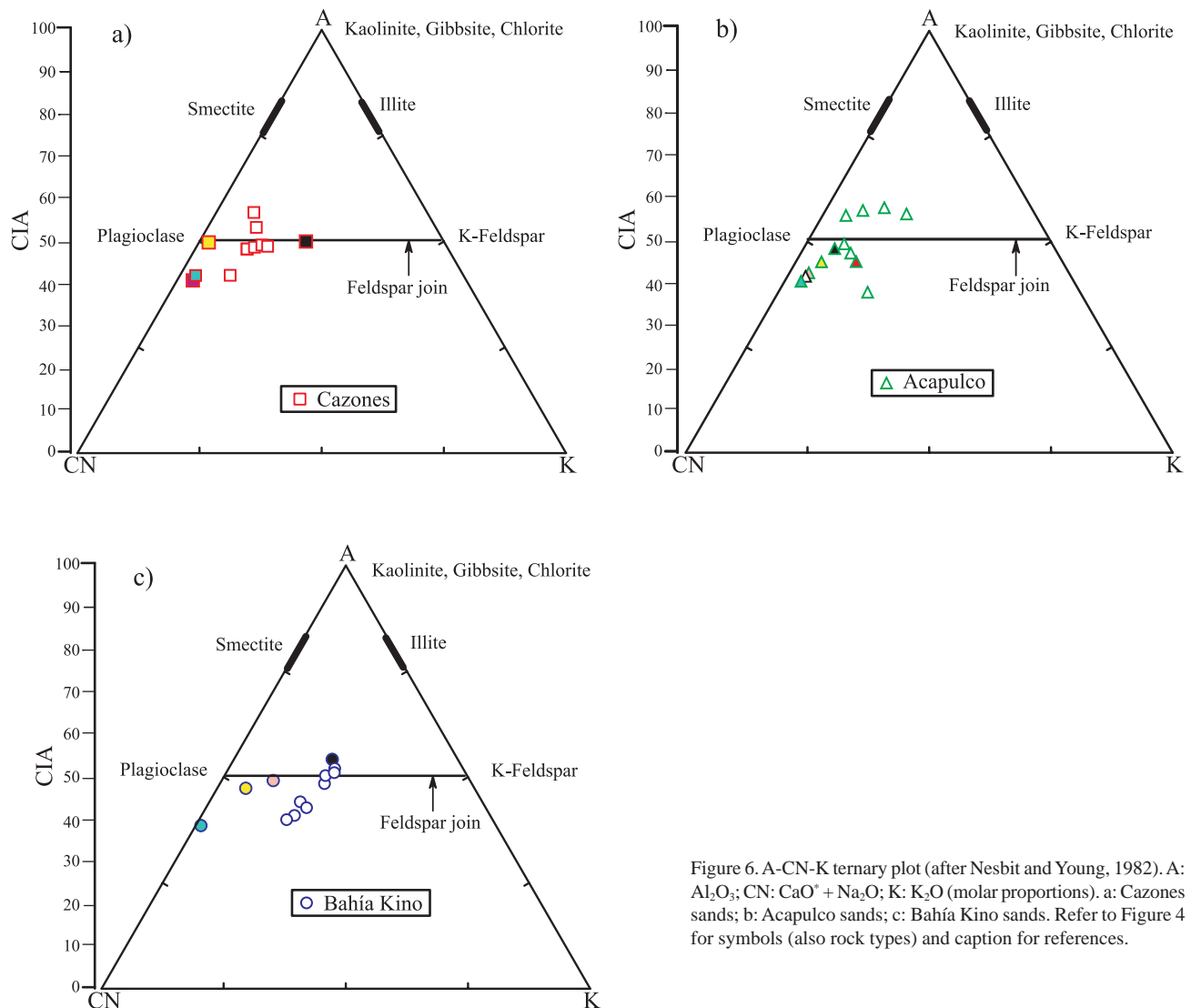


Figure 6. A-CN-K ternary plot (after Nesbit and Young, 1982). A:  $\text{Al}_2\text{O}_3$ ; CN:  $\text{CaO} + \text{Na}_2\text{O}$ ; K:  $\text{K}_2\text{O}$  (molar proportions). a: Cazones sands; b: Acapulco sands; c: Bahía Kino sands. Refer to Figure 4 for symbols (also rock types) and caption for references.

Figure 5a are comparable to the average rhyolite (North-Central and Eastern MVB; no. 1, 3, and 4 in Figure 1) and andesite (part of Sierra Madre Oriental; no. 2 in Figure 1). It is observed that three felsic (Caz-1, Caz-3, and Caz-8) and three intermediate sands (Caz-7, Caz-5, and Caz-2) are with high negative Eu anomaly similar to rhyolite. The other two felsic sands (Caz-4 and caz-6) are showing low negative Eu anomaly (Table 6), which are comparable to andesite source rock. Hence, the REE patterns and Eu anomalies indicate that the Cazones sands were probably derived from the mixing of rhyolite (75%) and andesite (25%) source rocks. In many studies, it has been shown that the Eu anomaly in clastic sediments is commonly regarded as inherited from the source rocks (e.g., Roddaz *et al.*, 2006; Kasanzu *et al.*, 2008).

Similarly, the REE patterns of Acapulco (Figure 5b) also support a mixing of source rocks like granodiorite (Guerrero State, no. 15 in Figure 1), dacite and andesite (both are from Sierra de Chichinautzin volcanic field, no.

7-14 in Figure 1). However, the differences in  $\Sigma\text{REE}$  contents within Acapulco sands are wider, as discussed in the previous section. The intermediate sand (Aca-6) is higher in  $\Sigma\text{REE}$  content than the other sand samples. Two felsic sands (Aca-7 and Aca-5) have  $\text{Eu}/\text{Eu}^*$  ratio of 1.137 and 0.939, respectively. A large negative Eu anomaly is observed in the samples Aca-2 (mafic sand), Aca-3 (felsic sand), and Aca-6 (intermediate sand), and their REE patterns are comparable to average granodiorite. The REE patterns for the remaining felsic sands are comparable to the average dacite and andesite. These differences indicate that the granodiorite (40%), dacite (40%), and andesite (20%) contributed sediments to the Acapulco sands.

The differences in REE patterns between felsic and intermediate sand samples are lesser in Bahía Kino sands than in Cazones and Acapulco sands. The Bahía Kino sands (Figure 5c) are comparable to the average rhyolites (Central Sonora and Isla San Esteban; Vidal-Solano *et al.*, 2007 and Desonie, 1992, respectively; no. 18 and 19 in Figure 1) and

granites (Laramide and coastal Sonora granites; Valencia-Moreno *et al.*, 2001, 2003; no. 17 and 16 in Figure 1), with clear negative Eu anomaly ( $\text{Eu}/\text{Eu}^* = 0.726 \pm 0.040$ ,  $n = 8$ ). However, considering the  $\Sigma\text{REE}$  content and the size of the negative Eu anomaly, these sands are very similar to the Laramide and coastal Sonora granites. This implies that the beach sands of Bahía Kino received a major contribution from felsic (100%) parent rocks.

## CONCLUSIONS

Geochemical investigations on the beach sands for the three study areas (Cazones, Acapulco, and Bahía Kino) indicate broad differences among them. The percentage of quartz is higher in Bahía Kino sands (~48–83%) than in Cazones (~22–48%) and Acapulco (~20–48%) sands. The differences in source rocks for the three study areas are also traced by  $(\text{SiO}_2)_{\text{adj}}$  content,  $\text{K}_2\text{O}/\text{Na}_2\text{O}$  and  $\text{SiO}_2/\text{Al}_2\text{O}_3$  ratios. The average CIA values (~38–58) indicate a weak weathering in the source area. A steady state weathering trend identified in AC-N-K plot for the Cazones and Acapulco sands occurs where climate and tectonism vary greatly and results in the production of chemically diverse sediments. On the other hand, the non-steady state weathering interpreted for Bahía Kino sands indicates balanced rates of chemical weathering and erosion, which produce compositionally similar sediments over a long period. The zircon geochemistry did not affect the REE distribution and its patterns in the studied sand samples, although the presence of ilmenite minerals might explain the REE geochemistry of some Acapulco sands. The comparison of REE patterns and its Eu anomalies to the source rocks reveal that the sand samples were derived more from felsic rather than from intermediate source rocks: (1) Cazones sands composed of detrital components derived from rhyolite (75%) and andesite (25%); (2) Acapulco sands derived from granodiorite (40%) dacite (40%) and andesite (20%); (3) Bahía Kino received a major contribution from granites (100%). This suggests that REE patterns and Eu anomalies are well preserved in the beach sands and are highly reliable indicator of source rocks, even though the geochemical composition can be affected by processes such as hydraulic sorting during transportation.

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