Sand composition in an Iberian passive-margin fluvial course: the Tajo River

Emilia Le Pera[a,*], José Arribas[b]

[a]*Consiglio Nazionale delle Ricerche-Istituto di Ricerca per la Protezione Idrogeologica, Sezione di Cosenza, Via Cavour, 4-6, 87030 Roges di Rende (CS), Italy*

[b]*Departamento de Petrología y Geoquímica, Facultad de Ciencias Geológicas, Universidad Complutense de Madrid, C/Josè Antonio Novais s/n, 28040 Madrid, Spain*

Abstract

The Tajo River, the 10th largest river in Europe, drains part of the western passive margin of Europe that includes multiple tectonic elements of the Iberian plate. Modern fluvial sand composition in the Tajo River drainage basin reflects the nature of the source region, which lies in the central part of the Iberian Peninsula. Four fluvial petrographic provinces (A, B, C and D) can be established in the Tajo drainage basin, corresponding well with the four principal structural units drained: (1) the Iberian Range; (2) the Hesperian massif; (3) The Tertiary Tajo basin; and (4) the Neogene Santarem–Lisboa basin.

Province A corresponds to the Tajo River head and is characterized by quartzolithic sedimenticlastic sands ($Qm_{67}F_4Lt_{29}$ and $Rs_{79}Rg_3Rm_{18}$). These sands have been derived from diverse Mesozoic siliciclastics and carbonates of the Iberian Range. *Province B* appears in the upper reaches of the Tajo River course and is quartzofeldspathic ($Qm_{57}F_{34}Lt_9$) with diverse rock fragments ($Rs_{34}Rg_{23}Rm_{43}$). Sources are Hercynian granitoids and metasediments and Neogene clastics and minor carbonates of the Tertiary Tajo basin. *Province C* extends along the middle course of the Tajo River with quartzofeldspathic metamorphiclastic sand modes ($Qm_{60}F_{33}Lt_7$; $Rs_4Rg_{21}Rm_{75}$). The sources are metamorphic rocks intruded by plutonites of the Hesperian Massif. *Province D* is quartzofeldspathic ($Qm_{55}F_{39}Lt_6$) with a dominance of phaneritic rock fragments ($Rs_5Rg_{33}Rm_{62}$) and corresponds to the lower reaches of the Tajo River, where siliciclastic deposits of the Neogene Santarem–Lisboa basin are the main sources. Sands plot on provenance-discrimination diagram (QmFLt) within the recycled-orogen field (Tajo River head) and continental-block fields (upper, middle and lower course). In addition, we have proven the usefulness of the *RsRgRm* diagram to discriminate the defined fluvial provinces, originating from heterogeneous parent-rock textures and mineralogy.

Climate does not exert any strong influence on the petrogenesis of the Tajo River drainage basin sand, and erosion in the source areas may be described in terms of weathering-limited denudation regime. By contrast, mixing with tributary supplies is the main process that modifies composition in the Tajo River sand. The establishment of fluvial provinces related to the main bedrock structural units reflects the great relevance of tributaries from each province in the generation of the Tajo River sand and the low significance of inherited sandy load from previous provinces.

* Corresponding author. Tel.: +39 984 835528; fax: +39 984 835319.
E-mail addresses: emilia.lepera@irpi.cnr.it (E. Le Pera), arribas@geo.ucm.es (J. Arribas).

The abundance of granitoid rock fragments (RsRgRm%Rg) in fluvial sand of both tributaries and main channel of the Tajo River drainage basin faithfully represents the relative abundance of granodiorite+monzogranite bedrock exposure in each subbasin. Metasedimentary and metamorphic bedrock outcrop area is overrepresented by metamorphic rock fragments (RsRgRm%Rm) in both sand from tributaries and from the Tajo main trunk river. This is manifested by differences of 18 23% between means of metasedimentary outcrop area and the RsRgRm%Rm mean in the sand from Provinces B and C+D, respectively. Sedimentary (mainly carbonate) outcrop area is underrepresented or not represented by sedimentary rock fragments (RsRgRm%Rs) in sand of the Tajo River. This underrepresentation causes a difference between means of sedimentary outcrop area and the RsRgRm%Rs mean of 21%, 17.1% and 10.7% in sands from Province A, B and C+D, respectively. This fact confirms the rapid loss of these grains during transport because of their labile nature.

Keywords: Sand; Petrofacies; Tajo River; Provenance; Fluvial basin

1. Introduction

Various factors combine to produce clastic assemblages found in modern and ancient sediments (Suttner, 1974). These factors include source-rock composition, tectonics, climate and relief, which together are being referred to as provenance (Dickinson, 1970; Basu, 1985). Modern fluvial and marine sands are especially suited for provenance studies, through framework composition (e.g., Dickinson and Valloni, 1980; Grantham and Velbel, 1988; Ibbeken and Schleyer, 1991; Johnsson et al., 1991; Ingersoll et al., 1993; Critelli et al., 1997; Le Pera et al., 2001), accessory minerals (Mange-Rajetzky, 1981; Morton and Smale, 1991) or both (Arribas et al., 2000; Garzanti et al., 2000), because of the absence of major post-depositional processes and presence of the physiographic and climatic correlation between source area and sedimentary basin (Valloni, 1985).

Understanding actualistic petrofacies, based on sand petrology of large river systems, is important for questions of global significance such as relating sand composition to relief, source rock, climate (Potter, 1978a,b; Johnsson et al., 1988; DeCelles and Hertel, 1989; Blasi and Manassero, 1990) and plate tectonics (Dickinson and Suczek, 1979).

The Tajo River, the 10th largest river in Europe, drains part of the western passive margin of Europe that includes multiple tectonic elements of the Iberian plate (Fig. 1). The geologic, geomorphologic and climatic variabilities of the drainage basin provide an actualistic setting in which to study the relationships between sand composition and possible major factors operating within the sedimentary system on a continental scale.

Small-scale studies on sand composition have been carried out in tributaries of the Tajo River (i.e., Tortosa et al., 1989; Palomares and Arribas, 1993; Arribas et al., 2000; Arribas and Tortosa, 2003). These studies have stressed the relevance of factors influencing sand composition that operate during the first stage of sand generation (i.e., lithology, slope and mixing processes).

The present study, focused on a larger scale, has importance to a general understanding of the quantification of how relief, climate and source rock affect the petrogenesis of siliciclastic sand, produced on a continental block. This knowledge is a prerequisite to assessments of provenance based on clastic composition in the geological record. In addition, interpretation of ancient sandstones from passive continental margins can be improved by analogy with this actualistic provenance study.

2. Geological setting

The Tajo River has an asymmetric drainage basin (Elorza Gutierrez, 1994) located in the central part of the Iberian Peninsula (Fig. 1). The basin is nearly 660 km long and up to 140 km wide, being one of the big European Atlantic rivers. The Tajo River (1007 km long) flows westward, wandering across several structural units of the Iberian plate and debauching on the Iberian western passive margin (Fig. 1). In addition, a well-developed abyssal plain

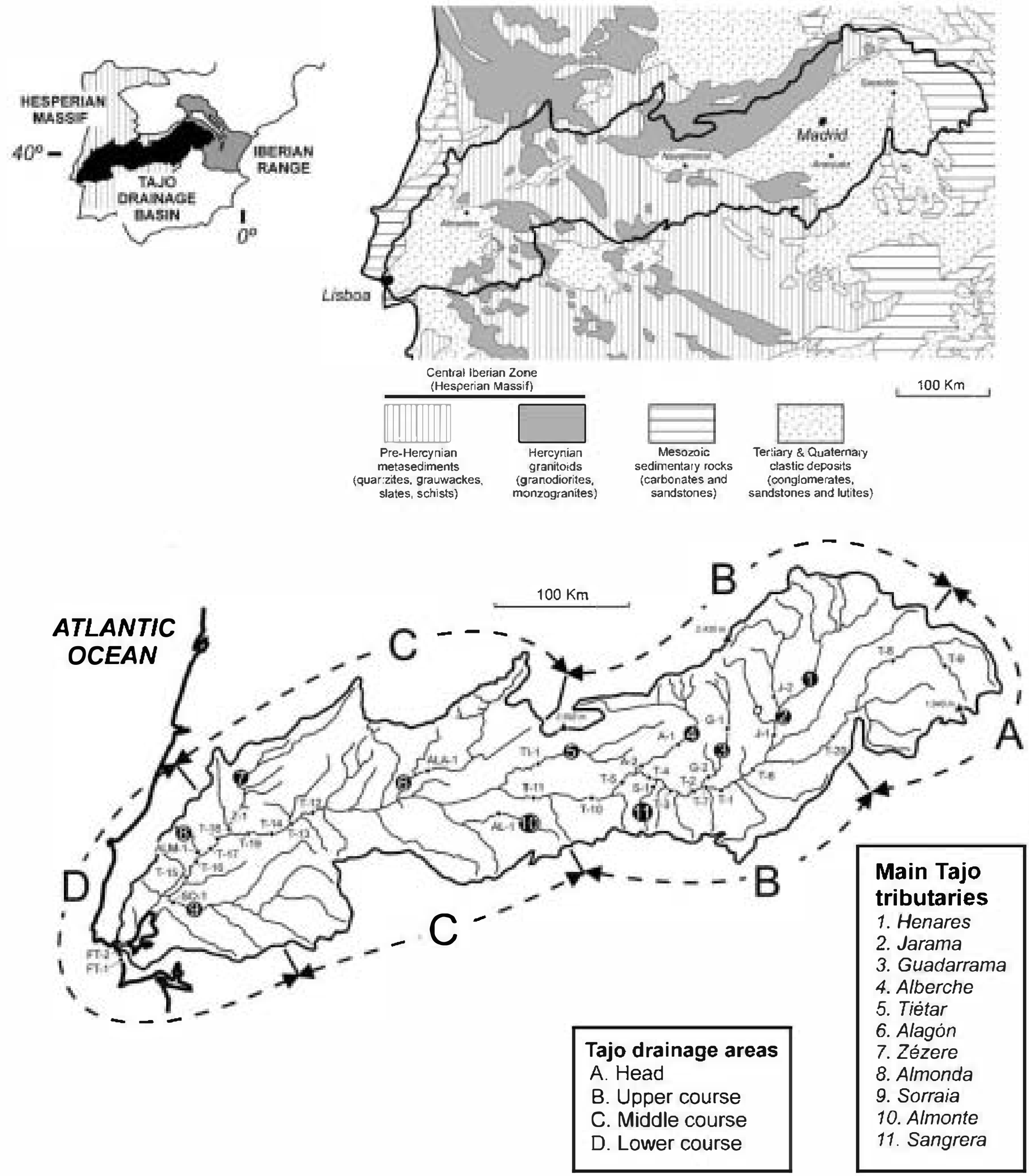

Fig. 1. Map showing generalised bedrock geology and fluvial drainage network of the Tajo River basin. Numbered dots indicate the location of samples.

receives the final detritus yielded by the Tajo drainage system. The principal river valley mainly incises Neogene tabular deposits and some pre-Hercynian metamorphic and crystalline terrane (Aparicio et al., 1975). Four portions of the Tajo drainage basin with distinctive morphological and hydrological characteristics can be distinguished based on structural units: (1) the Iberian Range (at the head); (2) the Tertiary Tajo basin (upper course); (3) the Hesperian Massif (middle course); and (4) the Neogene Santarem–Lisboa basin (lower course) (A, B, C and D zones in Fig. 1, respectively).

The Tajo river head (from its source to Sacedón) is located in the Iberian Range, a NW–SE-trending Alpine chain consisting of Mesozoic sedimentary strata (Triassic feldspathic sandstones, Jurassic and Cretaceous marine carbonates and subarkosic sandstones). Streams and river courses are narrow, cutting the sedimentary bedrock without a well-developed alluvial plain (Arribas and Tortosa, 2003).

The Tertiary Tajo basin, in the upper course, contains Neogene continental-clastic, carbonate and evaporite tabular formations. Neogene clastics derived from the Alpine uplifted surrounding areas (Iberian Range at the east, the Central System at the north and the Toledo Mountains at the south). In this track (from Sacedón to Navalmoral), the Tajo River and its main tributaries develop wide alluvial plains with several Quaternary terraces and meander bars. In this segment, the northwest watershed of the drainage area is situated in the Central System, a mountainous range that consists of a large exposure of granitoids that intrude pre-Hercynian metamorphic basement.

The middle course (from Navalmoral to Abrantes) cuts low-grade metamorphic rocks (Precambrian graywacke and slates, Cambrian slates and quartzites and associated intruding granitoids) from the Central Iberian Zone in the Hesperian Massif. The Tajo River is deeply incised in this area, showing little development of alluvial deposits.

The lower course of the Tajo River (from Abrantes to Lisboa) is developed on the Santarem–Lisboa Neogene basin. Again, the tabular arrangement of the Tertiary detrital deposits favours the wandering course of the Tajo River, with a wide alluvial plain with meander bars and a well-developed system of Quaternary terraces. Estuarine deposits are also present near the river mouth. Head streams of tributaries at the north and south also drain Jurassic carbonate and metamorphic terranes from Hesperian

Table 1
Physiographic and climatic characteristics of the Tajo River drainage basin

Topography					
	Northern tributaries (mean max. altitude) (m)	Southern tributaries (mean max. altitude) (m)	Tajo mainstem (mean altitude) (m)	Northern divide distance (mean) to Tajo mainstem (m)	Southern divide distance (mean) to Tajo mainstem (m)
Zone A	1455	1417	1204	10200	34040
Zone B	2000	1110	443	89360	34040
Zone C	1479	760	182	51060	46800
Zone D	569	405	56	23400	72340

Climate					
	Annual average temperature (°C)	Annual average rainfall (mm)	Climate		Leaching factor*
Zone A	7.5	750–1200	humid temperate		50.25–95.25
Zone B (nth)**	7.5	750–1200	humid temperate		50.25–95.25
Zone B (sth)**	12.5	500	warm temperate		8.75
Zone C	12.5	500	warm temperate		8.75
Zone D	16	750–1200	warm to humid temperate		22.2–67.2

* Leaching factor=mean annual precipitation (cm) minus 3.3×mean annual precipitation (°C) (Crowther, 1930).

** nth=northern area; sth=southern area.

Massif, respectively, cropping out at the edges of the Neogene basin (Fig. 1).

The main topographic data that characterize the Tajo drainage basin are summarized in Table 1. The elevation of the Tajo River drainage basin varies from sea level to more than 2000 m. The higher altitudes correspond to watershed in the Central System (Mount Almanzor, 2592 m; Mount Peñalara, 2430 m) and in the Iberian Range (Mount San Felipe, 1840 m). Slopes vary throughout the basin. Thus, at the head (Iberian Range), mean slope ranges from 20% to 30% (Arribas and Tortosa, 2003). In the upper course, slopes at head streams of tributaries in the Central System are more gentle, from 10% to 30% (Palomares and Arribas, 1993; Arribas et al., 2000). Slope values drop drastically where the Tajo River and its tributaries cut into the Tertiary basin deposits (Tertiary Tajo basin in the upper course and Tertiary Santarem–Lisboa basin in the lower course). In the middle course, streams flowing across the metamorphic bedrock of the Hesperian Massif show more gentle slopes than in the Central System.

The climates at the head, upper and middle courses can be considered as continental Mediterranean, while in the lower course, the influence of the Atlantic Ocean reduces the thermal amplitude and increases precipitation (Atlas Nacional de España, 1993) (Table 1). High values (750–1200 mm) of mean annual precipitation occur at the highest altitudes of mountainous areas (at the head and at the Central System) and in the lower part of the basin. At the lowlands of the inner the basin, mean annual precipitation decreases to less than 500 mm. In addition, mean annual temperature in the interior areas differs from high to lowlands (from 7.5 to 12.5 °C, respectively), but increasing to 16 °C along the Atlantic coast.

According to these climatic parameters, and following Wilson's (1969) criteria, weathering varies from "moderate chemical weathering with frost action" in the highest zones of the Central System to "moderate chemical weathering" in the lowlands of the basin (Table 1 and Fig. 2). Furthermore, a more rigorous attempt to quantify the total extent of weathering has been made through the calculation of the weathering index (WI) proposed by Weltje (1994), which integrates present-day climate and physiography of sediment sources (Weltje et al., 1998). The value of the weathering index for the Tajo drainage basin ranges from 0 in the upper reaches of the basin to 1 in the lower reaches and river mouth, implying that the parent rock is unweathered or slightly weathered. As a consequence, the rate of bedrock removal by transport processes precludes the development of thick soil horizons. Thus, the denudation regime can be considered as close to a weathering-limited type (Johnsson, 1993), and sand detrital modes can be safely assumed to reflect primary composition of parent rocks (e.g., Basu, 1976; Mack and Jerzykiewicz, 1989; Girty and Armitage, 1989; Palomares and Arribas, 1993; Weltje et al., 1998; Arribas et al., 2000; Garzanti et al., 2000; Critelli et al., 2003).

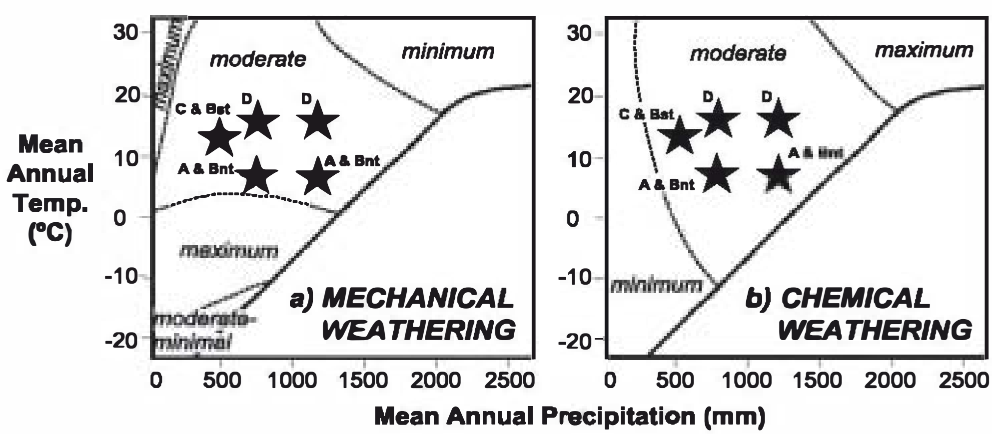

Fig. 2. Relationships between climate (precipitation and temperature) and mechanical and chemical weathering (A, B, C, D=Tajo River drainage areas of Fig. 1; nt=northern tributaries; st=southern tributaries) (after Wilson, 1969).

Vegetation in the study area is variable and correlated with altitude and precipitation. In the highlands of the Tajo basin, the mountains of the Iberian Range carry coniferous trees; in the middle-lower course, oaks, cork trees and drought-resistant plants are widespread, commonly reduced to scrub status (*matorral*). Tajo estuary's cultivated land is devoted to cereal farming, and everywhere are olive trees and vineyards (Atlas Nacional de España, 1993).

The Tajo flows mostly through semiarid lands, and government efforts have been dedicated to increasing land irrigation and creating hydroelectric power in its basin (Atlas Nacional de España, 1993). Major efforts to harness the Tajo and its tributaries for these purposes were undertaken from the 1960s, and by 1980, dams had been built.

3. Procedures

Thirty-four samples were collected (Fig. 1). Fourteen are sands from the main channel of the Tajo River point bars and side bars, 6 are sands from fluvial deposits of Holocene terraces of the Tajo River and 12 are sands from the Tajo principal tributaries. In addition, two sand samples were collected from the Tajo estuary system.

Sand samples were washed with dilute H_2O_2 to remove organic matter, air-dried and sieved (using 1 phi intervals) to obtain the medium-sand fraction (0.50–0.25 mm). This fraction was cemented with epoxy resin, thin-sectioned, etched with HF and stained by immersion in sodium cobaltinitrite solution to allow identification of feldspars. Alizarine and potassium Fe-cyanide solutions were also used for carbonate grains identification. To analyse the modal composition of the sand, 300 points were counted on each thin section following the *Gazzi–Dickinson* method (Gazzi, 1966; Dickinson, 1970; Ingersoll et al., 1984; Zuffa, 1985). Sixty categories of grains were distinguished for the sand carried by the Tajo River main channel and its tributaries (Table 2). In addition, a quantitative analysis of main drained source rocks was conducted for each mainstem and tributary sample site (Table 3). These data were acquired using digital (topographic and geologic) maps, following the method developed by Montesinos and Arribas (1998), Arribas et al. (2000) and Le Pera et al. (2001). The contrast between sand composition and outcrop area of each source rock provides useful information about the persistence or dilution of each grain type (Arribas et al., 2000; Arribas and Tortosa, 2003).

4. Grain types

Grain types of the Tajo River and its tributaries are briefly described below in order of decreasing abundance.

4.1. Quartz (Q)

Quartz was divided into monocrystalline grains, coarse-grained (phaneritic) rock fragments (metamorphic, plutonic and sedimentary rock fragments) and fine-grained polycrystalline quartz with tectonic fabric, presumably derived from the low- to high-rank metamorphic rocks of the Central System (Tortosa et al., 1991), or without tectonic fabric. Some samples of the Tajo main channel sand include sedimenticlastic quartz particles, including monocrystalline quartz with evaporite inclusions and quartz within arkose grains, documenting recycling from the Mesozoic sedimentary formations cropping out in the Iberian Range (Arribas and Tortosa, 2003).

In addition to these varieties, quartz grains with embayments are also present in the downstream sand of the Tajo River, indicating, probably, processes of in situ weathering in a soil profile (Crook, 1968; Cleary and Connolly, 1971; Le Pera et al., 2001).

4.2. K-feldspar (K) and plagioclase (P)

K-feldspar and plagioclase occur almost entirely as unweathered single crystals; minor amounts are contained within granite, gneiss and arkosic phaneritic grains. K-feldspar is more abundant than plagioclase (P/F ratio<0.50; Table 2). Most potassium-feldspar grains are orthoclase, but minor amounts of microcline are also present.

4.3. Labile lithic fragments (L)

Labile lithic fragments are represented by aphanitic grains (predominantly schists and phyllites). Sedi-

Table 2
Results of petrographic modal analysis

			Tajo River (mainstem)																						Tajo River tributaries												
			T-9	T-8	T-20	T-6	T-1	T-7	T2	T-3	T-4	T-5	T-10	T-11	T-12	T-13	T-14	T-19	T-18	T-17	T-16	T-15	FT-2	FT-1	J2	J1	G1	G2	A1	A2	A11	S1	Ti1	Ala1	Alm1	SO1	Z-1
NCE	Q	Quartz (single crystal)	194	67	167	114	129	122	104	135	139	119	107	141	120	105	167	107	92	124	121	118	123	154	105	117	105	105	90	90	40	91	97	102	122	112	98
		Polycrystalline quartz with tectonic fabric	0	0	0	2	0	3	0	1	0	2	2	0	0	1	2	0	2	2	1	1	0	2	0	1	0	3	0	1	2	0	1	0	1	2	0
		Polycrystalline quartz without tectonic fabric	1	1	0	0	0	0	0	0	0	1	1	0	1	2	1	1	1	2	4	1	1	2	0	1	0	1	1	0	0	2	0	0	0	0	2
		Quartz in metamorphic r.f.	29	9	16	29	41	29	12	15	41	28	25	8	41	28	26	35	26	32	29	32	26	22	23	33	18	18	35	35	87	23	39	33	43	29	58
		Quartz in plutonic r.f.	0	0	0	1	3	1	1	6	3	1	1	0	1	1	0	0	1	0	0	0	0	0	2	0	0	3	2	4	0	0	2	1	0	0	0
		Quartz in plutonic/gneissic r.f.	4	0	4	32	3	12	3	8	5	10	18	3	12	8	3	10	8	21	14	0	6	4	18	15	4	12	10	22	0	7	18	8	16	12	10
		Quartz in sandstone	18	71	1	8	2	4	0	0	4	22	0	1	0	0	0	0	0	0	0	11	33	4	0	14	2	7	1	1	0	38	1	12	5	2	7
		Quartz with evaporitic inclusion	0	2	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	K	K-feldspar (single crystal)	10	4	16	56	63	77	65	74	57	44	74	60	64	72	58	71	89	68	70	83	42	32	85	74	95	97	89	70	1	65	67	59	54	64	38
		K-feldspar in metamorphic r.f.	0	0	0	3	4	0	0	1	4	0	1	0	1	4	0	1	0	1	1	0	0	0	3	0	0	1	4	3	0	0	1	2	2	0	3
		K-feldspar in plutonic r.f.	0	0	0	0	3	0	1	1	2	1	3	0	0	1	0	0	0	1	0	0	0	0	2	0	2	2	1	7	0	1	10	2	3	0	0
		K-feldspar in plutonic/gneissic r.f.	0	0	0	4	5	1	0	0	0	2	8	2	1	5	2	3	3	7	3	4	0	1	11	8	8	2	9	6	0	4	2	5	7	5	0
		K-feldspar in sandstone	2	3	0	5	0	0	1	0	1	0	0	2	0	0	0	0	0	0	0	0	4	2	0	5	1	1	0	2	0	20	0	7	1	0	1
	P	Plagioclase (single crystal)	2	0	0	15	26	22	47	23	14	28	39	27	21	27	16	22	22	19	23	26	5	2	24	19	49	35	33	30	0	30	29	14	13	22	16
		Plagioclase in metamorphic r.f.	0	0	0	0	2	0	0	0	3	1	0	0	1	1	1	0	1	0	1	0	0	0	0	0	1	1	0	0	1	1	2	1	2	0	2
		Plagioclase in plutonic r.f.	0	0	0	0	1	0	1	1	6	1	1	0	1	0	0	2	0	0	0	0	0	0	0	0	0	3	3	3	0	0	0	1	1	0	1
		Plagioclase in plutonic/gneissic r.f.	0	0	0	1	0	1	2	2	2	0	1	1	2	1	0	0	4	6	1	3	0	0	2	1	5	5	3	6	0	1	1	1	1	1	0
		Plagioclase in sandstone	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0
	M	Biotite (single crystal)	0	0	0	0	1	3	19	3	0	4	3	4	3	8	4	1	13	3	7	2	0	0	1	0	2	1	7	3	0	3	7	6	2	0	8
		Muscovite (single crystal)	2	0	0	0	1	0	5	2	0	4	2	2	4	3	0	0	4	2	4	2	0	0	0	0	1	4	1	0	0	2	6	3	1	2	4
		Chlorite (single crystal)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0
		Mica in metamorphic r.f.	0	0	0	3	1	0	0	0	0	0	2	2	0	3	2	2	3	0	3	4	0	0	3	2	2	2	1	4	3	0	4	0	0	2	12
		Mica in plutonic r.f.	0	0	0	0	0	1	1	1	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0

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Table 2 (*continued*)

			Tajo River (mainstem)																						Tajo River tributaries												
			T-9	T-8	T-20	T-6	T-1	T-7	T-2	T-3	T-4	T-5	T-10	T-11	T-12	T-13	T-14	T-19	T-18	T-17	T-16	T-15	FT-2	FT-1	J2	J1	G1	G2	A1	A2	Al1	S1	Ti1	Ala1	Alm1	SO1	Z-1
		Mica in plutonic/ gneissic r.f.	0	0	0	1	0	0	1	1	0	1	0	0	2	0	1	0	3	2	1	1	0	0	0	0	2	0	1	3	0	1	6	3	1	0	1
	L	Volcanic lithic with microlitic texture	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
		Phyllite	0	1	0	10	2	6	4	0	3	1	2	0	10	8	6	4	10	2	6	2	0	0	7	2	0	0	1	0	51	0	0	5	4	2	4
		Fine-grained schist	0	2	0	6	1	0	1	4	4	2	1	3	6	13	5	8	8	5	3	6	5	2	3	4	1	1	4	3	106	2	1	23	4	4	20
		Impure chert	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Siltstone	5	0	0	0	1	0	0	0	1	1	0	0	0	0	1	0	1	0	0	1	0	1	0	0	0	0	0	0	0	0	0	1	1	20	1
		Shale	0	0	0	0	0	0	0	0	0	0	0	1	4	2	0	3	8	1	6	1	0	0	0	0	0	0	0	0	0	0	0	3	3	7	8
		Fine grained-sandstone (Fe-oxide matrix)	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Ot	Tourmaline	0	0	0	1	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	2	1	0	0	0	0	1	0	0	1	0	0	0
		Garnet	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1
		Apatite	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
		Sillimanite	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Epidote	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0
		Hornblende	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0
		Staurolite	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
		Heavy mineral in labile metamorphic r.f.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	1	0	0	5	0	0	0	0	0	1
		Opaque mineral (single crystal)	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	1	1	1
CE	CAL	Micritic limestone	4	34	26	2	0	10	14	12	6	12	1	14	0	0	0	0	0	0	0	0	0	7	0	0	0	0	0	0	0	0	0	0	0	0	0
		Sparitic limestone	1	13	6	0	0	0	1	2	0	3	1	0	0	0	0	0	0	0	0	0	2	1	0	1	0	0	0	0	0	0	0	0	0	0	0
		Microsparitic limestone	1	7	11	1	1	2	1	0	0	1	2	2	0	0	0	0	0	0	0	0	1	2	0	0	0	0	0	0	0	0	0	0	0	0	0
		Biomicrite limestone	2	5	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	2	0	0	0	0	0	0	0	0	0	0	0	0	0

	Biosparite limestone	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0
	Grainstone	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Calcite (single crystal)	4	10	15	0	1	5	14	0	1	2	0	0	0	0	0	0	0	0	0	0	12	14	1	1	0	0	0	0	0	0	0	0	0	0	0
	Fossil	3	9	2	0	1	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Silty-arenitic limestone	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Micrite and/or $CaCO_3$ cement within sandstone grain	5	10	4	0	1	0	0	1	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
DOL	Dolomite (single crystal)	3	2	5	1	0	0	0	2	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Dolostone	0	14	5	0	0	0	0	2	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Dolarenite	4	21	6	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Dedolomite	1	3	5	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Undetermined limestone	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CI	Bioclast	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	17	44	0	0	0	0	0	0	0	0	0	0	0	0	0
	Intraclast (micrite)	1	6	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Intraclast (microsparite)	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Palisade microsparite grain	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Alterite	1	0	0	1	0	1	1	0	0	0	1	2	2	0	4	0	0	1	0	0	0	0	0	0	0	0	0	0	3	0	0	0	1	3	0
	Nm	300	300	300	300	300	300	300	300	299	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300
	Qm	83	52	67	63	60	57	43	56	62	62	52	55	61	59	68	62	47	61	58	55	71	72	52	61	44	50	48	54	44	55	58	55	65	54	64
	F	5	2	5	29	34	34	41	35	32	29	44	32	32	30	27	33	43	35	35	41	20	14	44	36	56	50	50	45	1	43	41	33	30	31	23
	Lt	12	46	28	8	6	9	16	9	6	9	4	13	7	11	5	5	10	4	7	4	9	14	4	3	0	0	2	1	55	2	1	12	5	15	13
	Qm	94	96	92	69	64	62	51	61	67	68	54	62	66	57	72	64	52	63	62	58	78	83	54	63	44	50	48	55	98	57	59	63	69	64	74
	K	5	4	8	25	26	29	28	29	24	21	31	26	25	32	22	27	37	28	28	31	20	16	37	30	36	36	37	31	1	31	29	30	25	27	18
	P	1	0	0	6	10	9	21	10	9	11	15	12	9	11	6	9	11	9	10	11	2	1	9	7	20	14	15	14	1	12	12	7	6	9	8
	Lm	0	2	0	76	18	26	14	17	44	18	56	8	80	82	92	80	72	87	60	80	22	6	92	75	100	100	100	100	100	67	100	87	67	14	71
	Lv	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Ls	100	98	100	24	82	74	86	83	56	82	44	92	20	18	8	20	28	13	40	20	78	94	8	25	0	0	0	0	0	33	0	13	33	86	29
	Rg	5	0	4	33	13	22	17	33	23	15	46	13	23	21	17	23	23	47	28	31	4	8	43	27	43	44	40	52	0	14	47	17	30	17	11
	Rs	62	94	81	17	21	29	34	35	16	49	6	65	5	3	2	5	9	1	9	3	75	58	1	24	9	14	1	5	0	62	0	20	10	40	16
	Rm	33	6	15	48	66	49	29	34	61	36	48	22	72	76	81	72	66	52	63	66	21	34	56	49	48	42	59	43	100	24	53	63	60	43	73
	P/F	0.14	–	–	0.29	0.28	0.23	0.40	0.25	0.28	0.35	0.32	0.31	0.27	0.26	0.22	0.24	0.23	0.23	0.25	0.26	0.1	0.1	0.2	0.19	0.35	0.29	0.28	0.32	0.3	0.28	0.3	0.19	0.2	0.26	0.31

Table 3
Lithologic composition of source-drainage subbasins

		Surface of drainage subbasin (km^2)	Hercynian granitoids	Pre-Hercynian metasediments	Mesozoic sedimentary rocks	Tertiary and Quaternary clastics
Tajo River mainstem						
Zone A	T-9	710	0.0	0.0	100.0	0.0
	T-8	3053	0.0	0.0	96.4	3.6
	T-20	7325	0.0	0.0	53.2	46.8
Zone B	T-6	20732	8.9	5.8	28.7	56.6
	T-1	24206	8.6	7.3	24.5	59.7
	T-7	24843	10.1	7.8	23.8	58.2
	T-2	27342	11.8	7.2	21.9	59.1
	T-3	28343	13.1	8.0	20.5	58.4
	T-4	29578	13.0	9.7	19.9	57.4
	T-5	32878	17.4	8.9	18.1	55.6
	T-10	33891	17.0	11.5	17.5	53.9
	T-11	35397	17.0	14.5	16.8	51.7
Zone C	T-12	57253	22.3	31.2	10.1	36.4
	T-13	57712	22.7	30.8	10.4	36.1
	T-14	59346	23.0	31.6	10.1	35.2
	T-19	59731	23.0	31.7	10.1	35.3
Zone D	T-18	64959	22.3	34.3	10.1	33.3
	T-17	65263	22.2	34.2	10.1	33.6
	T-16	66027	21.9	33.8	10.0	34.3
	T-15	66203	21.9	33.7	10.0	34.5
	FT (1 and 2)	77536	21.1	32.5	9.2	37.2
Tajo River tributaries						
Zone B	J-1	2609	50.7	15.0	4.7	29.6
	J-2	8427	21.7	14.3	14.3	49.7
	G-1	1015	48.7	0.0	0.0	51.3
	G-2	2039	24.4	0.0	0.0	75.6
	A-1	2443	79.4	0.0	0.0	20.6
	A-2	2877	67.2	0.0	0.0	32.8
	S-1	424	0.7	95.6	0.0	3.7
	Ti-1	3625	51.8	5.9	0.0	42.4
Zone C	AL-1	1093	1.9	98.1	0.0	0.0
	ALA-1	4002	50.8	48.5	0.0	0.7
	Z-1	4659	16.8	65.0	13.7	4.5
Zone D	ALM-1	553	0.0	0.0	11.6	88.4
	SO-1	6658	27.2	41.6	0.0	31.2

mentary lithic grains are scarce (except for Sorraia River sand) and are mainly represented by shale and carbonate-cemented siltstone grains.

4.4. Limestone (CAL) and dolostone (DOL)

Total carbonate lithic fragments comprise diverse extrabasinal carbonate grains (CE; Zuffa, 1985), showing a wide spectrum of textures and compositions (Table 2).

4.5. Penecontemporaneous grains (CI)

These include bioclasts from the Tajo estuary (FT1 and FT2 samples) and intraclasts (CI; Zuffa, 1985). These latter grains have various types of calcite crystals of terrestrial carbonates (i.e., micrite, microsparite and radial palisadic microsparite crystal grains) interpreted as representing biomineralization (e.g., Freytet and Verrecchia, 1998). These grains are associated to the Tajo River head area (T8, T9 and T20 samples; Table 2), where weathering of Mesozoic carbonate rocks produces an important supply of carbonate waters (Arribas and Arribas, 1991; Arribas and Tortosa, 2003).

5. Sand detrital modes

Sand composition of different parts of the Tajo mainstem and tributaries reflects the geological setting of that area. Thus, and following the concept of 'petrographic provinces' introduced by Suttner (1974), the four main portions of the Tajo basin (Fig. 1) show distinctive sand compositional signals.

5.1. Province A

The head province is represented by sands of quartzolithic sedimenticlastic composition ($Qm_{67}F_4Lt_{29}$) and with very few or no feldspars (Fig. 3a; Table 2). Well-rounded multicycle quartz is the main clastic constituent (>50%; Fig. 4A). Lithic fragments are represented by diverse limestone and dolostone grains derived from the Mesozoic carbonates cropping out in

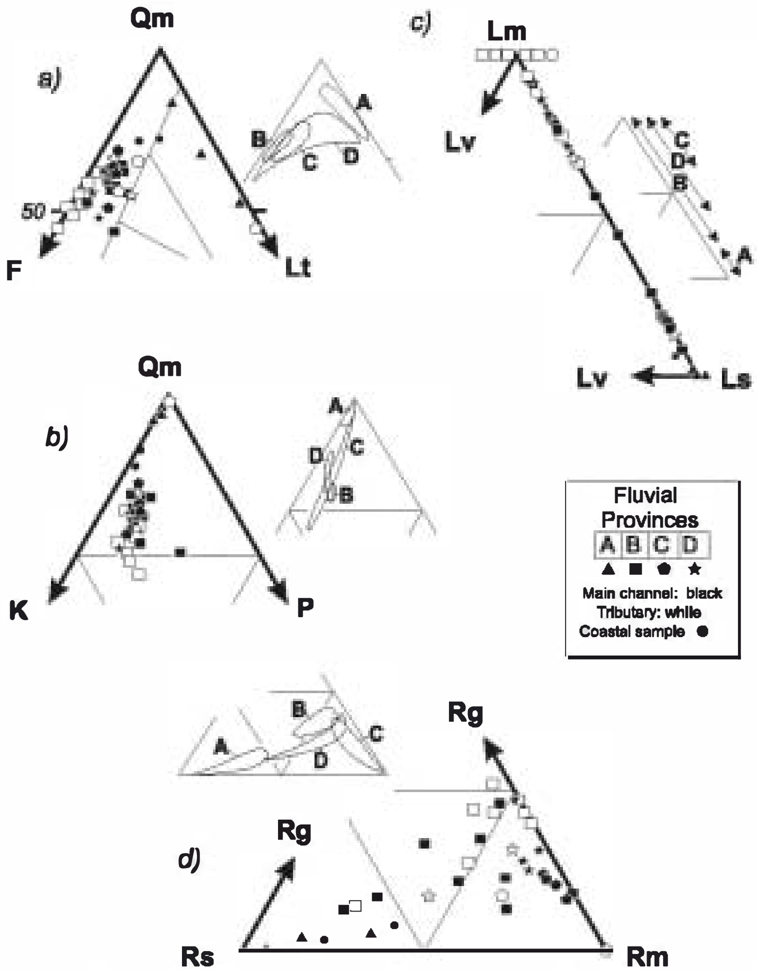
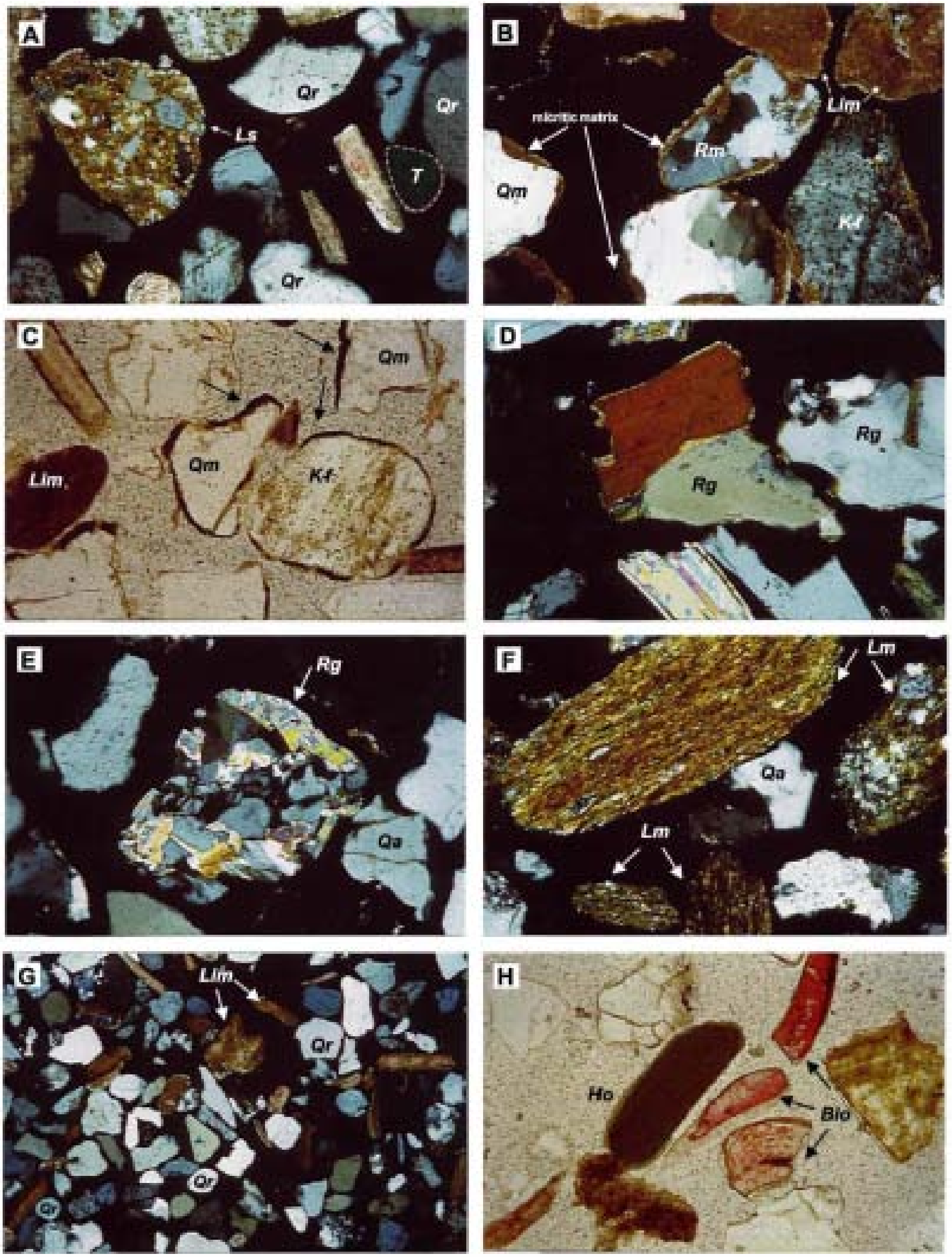


Fig. 3. Ternary diagrams showing sand composition from the Tajo River, its tributaries and estuary. Qm, monocrystalline quartz; F, feldspars; Lt, aphanitic lithic fragments; K, K-feldspar, P, plagioclase; Lm, metamorphic and metasedimentary aphanitic lithic fragments; Lv, volcanic aphanitic lithic fragments; Ls, sedimentary aphanitic lithic fragments; Rg, phaneritic plutonic rock fragments; Rs, aphanitic+phaneritic sedimentary rock fragments; Rm, aphanitic+phaneritic metamorphic rock fragments. Additional ternary diagrams show 90% confidence regions of the mean (Weltje, 2002) for each petrographic province.


A
Qr
Qr
Ls
T
Qr
B
micritic matrix
Lim
Rm
Qm
Kf
C
Qm
Lim
Qm
Kf
D
Rg
Rg
E
Rg
Qa
F
Lm
Qa
Lm
G
Lim
Qr
Qr
Qr
H
Ho
Bio

the Iberian Range ($Rs_{79}Rg_3Rm_{18}$) (Fig. 4B and C). Differences in Qm/Lt grain contents are controlled by the compositions of the sedimentary source rocks drained by the head-stream tributaries (Arribas and Tortosa, 2003). The labile behaviour of carbonate grains during transport is manifested by the increase of the ratio Qm/Lt from head-stream tributaries (0.66) to the Tajo mainstem (2.31). The recycled compositional characteristic at the Tajo head province persists when the mainstream flows across the Tertiary Madrid basin until the confluence of the Jarama River (near Aranjuez locality). Phaneritic rock fragments (Fig. 3d) include metamorphic rock fragments (Rm) and very few plutonites (Rg) related to recycled sedimentary detritus from Iberian Range Mesozoic rocks (Table 3).

5.2. Province B

Sand of the upper course of the Tajo River, from Sacedon to Navalmoral, is quartzofeldspathic, lithic-poor ($Qm_{56}F_{35}Lt_9$) but impure metamorphiclastic (mean of $Rs_{34}Rg_{23}Rm_{43}$) (Fig. 3a and Table 2). Sand modes in this province are plutoniclastic-derived (Fig. 4D and E) from the Hercynian granitoids and mixed with sedimenticlastic detritus provided by the Tajo River head. In addition, erosion of Tertiary sedimentary rocks from the Madrid basin produces an important percentage of the lithic population along the Tajo mainstem (Ls and Rs in Fig. 3c and d). Downstream destruction of sedimentary lithic grains should be expected from the Tajo River head, as observed by a number of studies on the relative persistence of labile grains during fluvial transport (e.g., Gazzi et al., 1973; McBride and Picard, 1987; Garzanti et al., 1998). However, dilution associated with plutoniclastic and metamorphiclastic northern tributaries probably is more significant (e.g., Critelli et al., 1997; Arribas et al., 2000). Fluctuation in the content of Ls and Rs grains along the Tajo mainstem reveals production of these grains by erosion of the Tajo River main course and southern tributaries and their dilution by plutoni-metamorphiclastic sand from the northern tributaries.

Feldspars grains are dominated by K-feldspar (Fig. 3b), reflecting a main contribution of the Hercynian granitoids from northern tributaries and of Tertiary to Quaternary siliciclastic sources for the fluvial sand (Table 3).

Sand of northern tributaries is quartzofeldspathic, with minor metamorphic lithics ($Qm_{52}F_{47}Lt_1$, Fig. 3a). These fluvial courses supply Lm grains in the Tajo mainstem (Fig. 3c). Tributaries sand modes in this province differ from Tajo main course sand modes by the greater compositional maturity of the latter. Mean sand composition in first-order streams is $Qm_{41}F_{55}Lt_4$ (Tortosa, 1988). Thus, feldspar loss (both K and P) is observed along the tributary channels, produced by mechanical abrasion during transport (Fig. 3b). In addition, incorporation of these tributary supplies by the Tajo main channel produces an increase of Qm grains, probably by dilution of feldspar grains when mixing with the quartzose sand provided by the Tajo head (Province A). Fluctuation in the content of Ls and Rs grains along the Tajo mainstem reveals production of these grains by erosion of the Tertiary Tajo basin by southern tributaries and by the mainstem.

5.3. Province C

Sand from this province, between Navalmoral and Abrantes (Portugal), is quartzofeldspathic ($Qm_{60}F_{33}Lt_7$) metamorphiclastic ($Rs_4Rg_{21}Rm_{75}$) (Fig. 3a and c; Table 2). Sedimentary source rocks seem to be relatively unproductive in lithics, and sedimentary lithics are underrepresented in the sand in relation to their outcrop area (over 40%; Table 3). In contrast, the metamorphic detritus (gneiss, schist, phyllite) makes up 80% of the sand (Fig. 4F) but

Fig. 4. Photomicrographs of diagnostic grains for the modern fluvial and beach sand provinces of the Tajo River basin. (A–C) Sedimenticlastic fluvial province (Province A): siliciclastic sedimentary lithic grain (Ls), limestone (Lim), rounded multicyclic quartz grains (Qr), well-round tourmaline grain (T), recycled metamorphic rock fragment (Rm) and K-feldspar (K-f) grain contained in a micritic matrix and well-preserved dark-brown rims of authigenic hematite around quartz and K-feldspar grains from the Triassic arkoses. (D and E) Quartzofeldspathic plutoniclastic fluvial province (Province B): first-cycle phaneritic rock fragments from the Hercynian granitoids (Rg) and angular quartz grains (Qa). (F) Quartzofeldspathic metamorphiclastic fluvial province (Province C): phyllite grains (Lm) and monocrystalline angular quartz grain (Qa). (G and H) Quartzose sedimenticlastic province beach sand at Tajo estuary (Province D): dominant rounded multicyclic quartz grains (Qr) with limestones (Lim), bioclasts (bio) and a well-rounded grain of green hornblende (Ho). All photos with crossed nicols except C (plane-polarized light). Field size of photomicrograph: 1×0.7 mm.

only 30.8–31.7% of the bedrock. Metamorphic detritus, especially gneiss and schist (Table 2), proves to be remarkably resistant to abrasion and mechanical breakdown and is enriched significantly compared with shale and siltstone grains (e.g., Le Pera and Critelli, 1997; Le Pera and Sorriso-Valvo, 2000). Mesozoic limestones, dominating in the upper reaches of the Tajo River, are absent in the sand of this province, suggesting that they undergo significant abrasion loss during nearly 400 km of fluvial transport (e.g., McBride and Picard, 1987; Garzanti et al., 1998; Arribas et al., 2000). The progressive dilution by quartzofeldspathic supplies from tributaries attenuates the upstream sedimentary signal. Tajo main stream and tributaries sand modes show similar compositions in both aphanitic and phaneritic lithic populations. This means that in the Tajo mainstem, little sand is inherited from the upriver province; it is mainly provided from the tributaries.

5.4. Province D

Sand from this province is quartzofeldspathic ($Qm_{55}F_{39}Lt_6$) metamorphiclastic ($Rs_5Rg_{33}Rm_{62}$) (Fig. 3a and c; Table 2). Sand modes are very similar to those of Province C, but have more abundant coarse-grained rock fragments. Sedimentary lithics appear in the sand of some tributaries; however, these grains tend to be diluted in the Tajo mainstream. Modal sand composition of two samples collected in the Tajo estuary system reveals a quartzolithic sedimenticlastic composition (Fig. 4G and H), with minor amounts of metamorphic lithics ($Qm_{72}F_{16}Lt_{12}$ and $Rs_{65}Rg_5Rm_{30}$). Sedimentary lithics are related to erosion of Jurassic carbonates cropping out in the Tajo River mouth. Minor amounts of coarse-grained rock fragments (metamorphic and plutonic) are observed in relation to the low preservation of these grains in coastal environments (e.g., Picard and McBride, 1993).

6. Discussion

6.1. Sources vs. sand composition

The Tajo drainage basin comprises four principal structural units, the orogenic belts of the Iberian Range and Hesperian Massif, the Tertiary Tajo basin and the Neogene Santarem–Lisboa basin. These latter two basins consist of broad regions of tabular siliciclastic, carbonate and evaporite deposits.

Sand composition within the Tajo River drainage area is diverse, which reflects the diverse source rocks of these units. Based on correlation between fluvial-sand and source-terrane composition, four fluvial petrographic provinces have been defined as regions where each of these distinct sand detrital modes is produced (e.g., Johnsson et al., 1991).

In addition, the influence of source-terrane composition upon sand composition in the Tajo drainage basin can be assessed quantitatively by comparing bedrock compositions in source areas with composition of sands from the Tajo River and from its tributaries (Table 3; Fig. 5). Because lithic grains are unequivocally related to their sources (e.g., Mack, 1981; Arribas and Tortosa, 2003), the contrast between their abundance in the sand and the areal extent of the source lithology in the drainage basin permits an evaluation of the extent to which each grain type is representative of that source. Contrast between sand compositional parameters (mainly lithics and rock fragments, L and R, respectively) and the proportion of their related rocks at the source reflects the level of representation of those sources in the sands (e.g., Arribas et al., 2000; Arribas and Tortosa, 2003). Thus, although Ls (aphanitic sedimentary lithics) and Rs (phaneritic+aphanitic sedimentary rock fragments) show a direct relationship with respect to the areal extent of their sources, these sources appear under-represented by the corresponding grains in the sand (Fig. 5). This fact is manifested in Fig. 5b, where arrows linking source-sand compositions are shown escaping the SED (Rs) pole in Province A, B and C. This lost of representation of sedimentary sources in the R population can be quantified as 21% in Province A, 17.5% in Province B and 10.7% in Province C+D that are the differences between means of sedimentary outcrop surface and RsRgRm%Rs. However, metamorphic lithics and rock fragments appear overrepresenting metamorphic source terranes. Over-representation can be evaluated as 18% in Province A, 23.1% in Province B and 18.1% in Province C+D, comparing mean from metamorphic outcrop area and the RsRgRm%Rm mean. The results of this study (Fig. 5; Tables 2 and 3) show that the percentage of metamorphic lithic grains (slates+schists+phyllites)

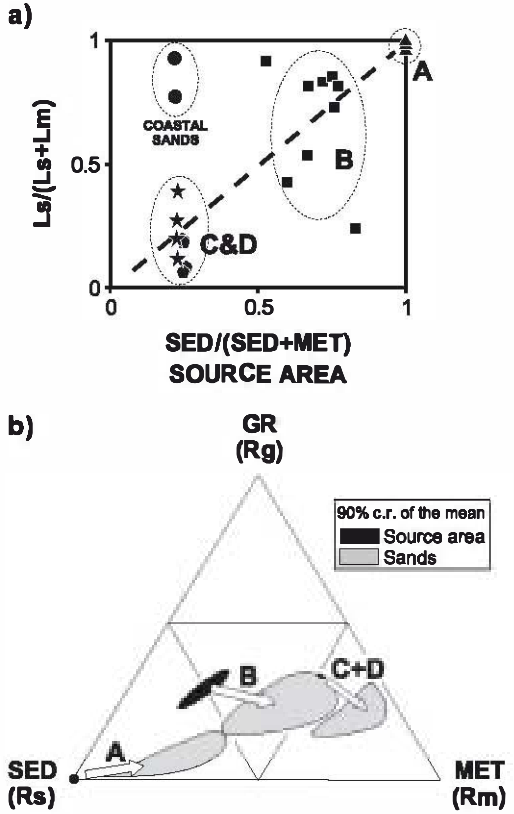


Fig. 5. (a) Plot of sedimentary aphanitic lithic fragments (Ls) in sands versus the corresponding indices of surface exposure of lithologies in the source area (sedimentary+metamorphic) of the Tajo River main channel; (b) GR (granitoid source rocks); SED (sedimentary source rocks); MET (metamorphic source rocks) showing the contrast between the relative proportions of source lithologies and relative proportions of rock fragments in sand (Rs: sedimentary rock fragments; Rm: metamorphic rock fragments; Rg: plutonic, granitic s.l., rock fragments). Arrows link source and sand composition. Fields represent 90% confidence regions of the mean (Weltje, 2002).

exceeds the relative proportion of these lithologies in the source area. This could imply that metamorphic detritus tends to concentrate in the lithic grain population, overrepresenting the proportion of this rock in the source area (e.g., Arribas et al., 2000). We have noted that the presence of nearly 30% of metasedimentary source rocks, with respect to other source lithologies (crystalline plus sedimentary; Table 3), guarantees 80% or more of Lm in the lithic sand population (LmLvLs%Lm). In contrast, labile grains, such as shale fragments, appear underrepresented in other modern fluvial sands of humid Mediterranean climatic setting (e.g., Gazzi et al., 1973; McBride and Picard, 1987; Le Pera and Sorriso-Valvo, 2000). Thus, concentration of Lm grains in the Tajo River drainage basin sands may be related to the semiarid climate and to the very steep slopes, factors acting to preserve these lithic grains (e.g., Cavazza et al., 1993; Arribas et al., 2000; Critelli et al., 2003). On the other hand, we have noted a poor representation of Ls grains in the sands (LmLvLs%Ls) compared with source lithology, outlined by a depletion of these grains from source to sand, evaluated on the order of more than half, when compared to the percentages of areal extent in the drainage areas. This is due to the poor capability of sedimentary rocks to generate lithic sand (e.g., Zuffa, 1987; Cavazza et al., 1993; Arribas et al., 2000) or rapid destruction of sedimentary lithic grains during transport (e.g., Ingersoll et al., 1993).

In sands from the upper Tajo River course (Provinces A and B), the proportions of phaneritic rock fragments correlate with proportions of coarse-grained rocks (plutonites) at the sources (nearly horizontal arrows in Fig. 5b). However, these sources are underrepresented by their corresponding rock fragments in sand from the lower course (Provinces C and D), suggesting mechanical breakdown process during transport. The shift of means from granitic sources to Rg grains in the corresponding sands is of +3% in Province A, −5.6% in Province B and −7.5% in Province C+D.

6.2. *The role of tributaries*

The recognition of fluvial petrographic provinces related to the main bedrock units underlain by the Tajo River drainage area reflects the relevance of tributaries from each province in the generation of the Tajo River sand and the low significance of inherited sandy load from upriver provinces. Dilution by mixing seems to be the main process that acts to modify sand composition in the Tajo River due to the different potential in sand generation at the source.

6.3. *Climate*

The leaching factor in the study area is not very high (Table 1), and thus climate does not exert any strong influence on the petrogenesis of Tajo River drainage basin sand (Fig. 2). Climate, an important control on the survival of feldspar detritus in the rock record (James et al., 1981; Critelli et al., 2003), could have played a role in the persistence of plagioclase and K-feldspar in the Tajo River basin sands. Multicycle sands derived from the Tertiary Tajo basin (Province B) and the Neogene Santarem–Lisboa basin (Province D) and first-cycle sands derived from the Hesperian Massif (Province C) contain approximately identical proportions of feldspars, probably as a result of no significant intense chemical weathering since, at least, Paleocene time. Also, the preservation of limestone and dolostone grains in Tajo River sands strengthens the assumption of a protracted arid or semiarid climate, promoting a high value of the sand generation index, as defined by Palomares and Arribas (1993), of carbonate source rocks (e.g., Arribas and Tortosa, 2003).

6.4. The Tajo River and continental passive-margin detrital modes

Tectonic processes impart distinctive compositional signatures to sediments, with different tectonic settings having characteristic sedimentary processes and sand provenance signatures for deep-marine (e.g., Dickinson and Valloni, 1980; Valloni and Maynard, 1981; Valloni, 1985; Arribas et al., 2003) and beach environments (Potter, 1984, 1986; Garzanti et al., 2001, 2003). However, very little research has been directed at modern sands of large rivers (e.g., Potter, 1978a; Ingersoll et al., 1993; Critelli et al., 1997; Potter et al., 2001), and many works have dealt with tropical river systems (Franzinelli and Potter, 1983; Potter and Franzinelli, 1985; DeCelles and Hertel, 1989; Johnsson, 1990), where often the tectonic signal may be virtually obliterated by the greater intensity of chemical weathering (Johnsson et al., 1988).

The composition of the Tajo drainage basin sands (second- and third-order sampling scale of Ingersoll, 1990) correlates with the tectonic setting of the source terranes (Fig. 3a). Although river sands show the effects of mixing from major tributaries entering the main trunk river on both sides, variations in tectonic setting are discernible from sands associated with the petrological provinces of the Tajo River drainage basin. Tajo River sands from Province A, derived from the fold-and-thrust terranes of the Iberian Range, are distinct from sands from block-faulted terranes of the Hesperian Massif and of the Tertiary Tajo basin and the Neogene Santarem–Lisboa basin (Provinces B, C and D; Figs. 3a and 6; Table 4). The fold-and-thrust terranes of the Iberian Range produce quartzolithic sand, with modest amount of feldspars. The block-faulted terranes produce quartzofeldspathic sands variable from metamorphi-plutoniclastic composition (Province B) to metamorphiclastic composition (Provinces C and D). The Tajo estuary sand (samples FT1 and FT2; Table 2 and Fig. 4G) is shifted toward a more quartzose composition. With large rivers, the sand provided to the shoreline is already homogenized and possibly stabilized (Ingersoll et al., 1993; Critelli et al., 1997). Similarly, coastal sand of the Tajo drainage basin is mineralogically more mature than associated fluvial provinces, but preserving information regarding source area (Figs. 3 and 6).

6.5. The Tajo River sands and other big-river sands

Modal compositions from the Tajo drainage basin sands are here compared with previously published data on modern big-river sands (Potter, 1978a). To discuss and compare our data to those of Potter's study, we had to refer to the QFR system, according to

Table 4
Composition of modern Tajo River drainage basin sand compared to data from literature

Reference	Location	Site sampling	Qm	F	Lt	Q	F	R
Present study	Tajo River drainage basin	Province A	67	4	29			
		Province B	57	34	9			
		Province C	60	33	7			
		Province D	55	39	6			
		Tajo estuary (FT2 sample)	71	20	9	47	18	35
		Tajo estuary (FT1 sample)	72	14	14	62	13	35
		Average 2 samples estuary	72	12	16	55	16	29
Potter (1978a)	Modern trailing-edge big rivers	Average 12 rivers				71	9	20
Potter (1978a)	Modern big rivers	Average 36 rivers				60	11	29
Marsaglia et al. (1996)	Western Iberia margin ODP Leg 149	Plio-Pleistocene deep-sea sand	75	20	5			

which any polymineralic grain is treated as a rock fragment (Table 4), instead of the QFL system (i.e., Dickinson, 1970).

The average sand of 36 modern big rivers studied by Potter (1978a) is a lithic arenite ($Q_{60}F_{11}R_{29}$) very close to Tajo's estuary average sand composition ($Q_{55}F_{16}R_{29}$). However, if we deal only with rivers debauching onto trailing continental margins, some differences emerge. Potter (1978a, Table 9) found that Atlantic-type trailing-edge sands average $Q_{71}F_{9}R_{20}$. Sand samples from the Tajo estuary, from the same tectonic setting, are less mature than average for trailing-edge sands, with $Q_{47}F_{18}R_{35}$ and $Q_{62}F_{13}R_{25}$ (Table 4). In contrast to Potter's (1978a) results for sands from trailing-edge big rivers, we have found a less mature composition for sand carried by the Tajo River (Table 4). This could be related to the fact that Potter's samples include rivers of tropical climate (Amazon, Orinoco, Paraná, Sao Francisco, etc.) that could bias compositions toward higher quartz contents even for first-cycle fluvial sands (e.g., Johnsson et al., 1988). Alternatively, this difference could be a function of variation in the analytical methods in that Potter (1978a, p. 423) sampled fine or fine-to-medium (and occasionally medium) sand, whereas our petrographic analysis was performed on the medium sand fraction (0.50–0.25 mm). Another possibility is that the Iberian Peninsula is not only a "trailing margin." Active or recently active tectonics (Alpine) of the Betic Cordillera, Iberian Range and Pyrenees complicate the tectonic classification.

Modern to recent sand derived from the western margin of Iberia is being deposited in the basin system of the Iberia Abyssal Plain, the location of Ocean Drilling Project sites 897 through 901, drilled on Leg 149 (Marsaglia et al., 1996). Plio-Pleistocene sand from sites 897 and 898 have quartzofeldspathic composition, with mean values of $Qm_{75}F_{20}Lt_{5}$; they are likely derived from the uplifted rift belt by way of the Mondego, Miño and Duero rivers (Marsaglia et al., 1996).

The Plio-Pleistocene deep-marine Iberia Abyssal Plain sand is related to a distinctive plate-tectonic setting (e.g., Dickinson and Valloni, 1980; Valloni and Mezzadri, 1984), similar to that of Tajo river-mouth sand (Table 4). The good match between onshore and offshore sand detrital modes confirms the effectiveness of Ingersoll's (1990) designation of sampling

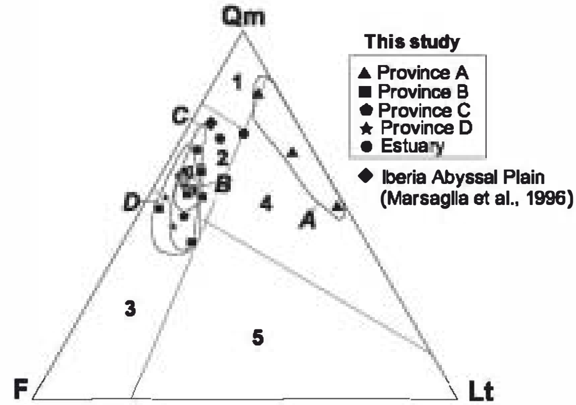


Fig. 6. Sand composition for the four fluvial provinces in the Tajo main stream and for the Tajo estuary and for the Plio-Pleistocene deep-sea sand of the Iberia abyssal plain studied in Marsaglia et al. (1996), plotted on QmFLt ternary diagram with superimposed provenance fields of Dickinson et al. (1983; 1: craton interior; 2: transitional continental; 3: basement uplift; 4: recycled orogen; 5: magmatic arc). Fields represent 90% confidence regions of the mean (Weltje, 2002) for provinces A, B, C and D.

order, with sand composition of large rivers and their mouths being useful in unequivocally discriminating plate-tectonic setting (e.g., DeCelles and Hertel, 1989; Johnsson et al., 1991; Ingersoll et al., 1993; Critelli et al., 1997) based on primary parameters (QmFLt) alone (Fig. 6).

7. Conclusions

Fluvial sands of the Tajo River drainage basin are derived from mixed source rocks of variable mineralogy and texture. They are composed mostly of pre-Hercynian to Hercynian metamorphic and plutonic rocks and Mesozoic to Quaternary siliciclastic and carbonate sedimentary rocks.

From the spatial distribution of the detrital modes of the sands, four distinct petrologic fluvial provinces are recognised along the main trunk river. Comparison of sand compositions from each fluvial province with actual source-terrane compositions yields remarkable agreement.

Province A corresponds to the Tajo River head and is characterized by quartzolithic sedimenticlastic sands ($Qm_{67}F_{4}Lt_{29}$) dominated by multicycle quartz particles and various limestone and dolostone grains ($Rs_{79}Rg_{3}Rm_{18}$). These sands have been derived from the erosion of diverse Mesozoic siliciclastic and carbonate terranes of the Iberian Range. The detritus has been carried and dispersed by bedrock rivers during times of rapid flow conditions and seasonal flooding.

Province B in the upper reaches of the Tajo River contains quartzofeldspathic sands ($Qm_{57}F_{34}Lt_{9}$) with diverse rock fragments ($Rs_{34}Rg_{23}Rm_{43}$). Sources are Hercynian granitoids and metasediments of the Central System and Toledo Mountains and Neogene clastics and minor carbonates of the Tertiary Tajo basin.

Province C extends along the middle course of the Tajo River. Sand modes are quartzofeldspathic ($Qm_{60}F_{33}Lt_{7}$), mainly metamorphiclastic ($Rs_{4}Rg_{21}Rm_{75}$). The source is the Hesperian Massif constituted by metamorphic rocks (slates, schists, quartzites and graywackes) intruded by several plutonites.

Province D corresponds to the lower reaches of the Tajo River. Sand modes are very similar than those of Province C ($Qm_{55}F_{39}Lt_{6}$) but show a greater content of phaneritic rock fragments ($Rs_{5}Rg_{33}Rm_{62}$). The main sources are the siliciclastic deposits of the Neogene Santarem–Lisboa basin. Finally, sand of quartzose sedimenticlastic composition ($Qm_{72}F_{16}Lt_{12}$ and $Rs_{65}Rg_{5}Rm_{30}$) is deposited along the Atlantic coast of the Tajo estuary, derived from the erosion of Mesozoic carbonates and Tertiary to Quaternary detrital sediments at the distal margin of the drainage basin.

On standard QmFLt and QtFL provenance-discrimination diagrams, sands plot within the recycled-orogen (Tajo River head) and continental-block fields (upper, middle and lower course), yielding a correct interpretation of the complex multiple tectonic setting of the source rocks. However, differences in provenance among the defined four provinces are not so clearly recognised when only aphanitic lithic fragments (LmLvLs) are considered. Thus, we suggest the use of the *RsRgRm* diagram in order to discriminate provenance among sand compositional groups originating from heterogeneous parent-rock textures and mineralogy.

Sedimentary processes affecting composition during transport can be deduced by comparing sand composition of tributary sands and the sand composition of the Tajo mainstem. Mixing seems to be the main process that modifies sand composition in the Tajo River sands, mainly in the upper and middle course (Provinces B and C). This process produces dilution of some components by the great potential for sand generation of tributary source lithologies. Little effect of mechanical abrasion has been identified, producing increases in compositional maturity (Provinces B, C and coastal zone of D) by the breakdown of sedimentary and phaneritic rock fragments.

Fluvial provinces related to the main bedrock structural units along the Tajo River course reflect the relevance of tributaries from each province in the generation of the Tajo River sand and the low significance of inherited sandy load from upriver provinces.

Contrast between sand compositional parameters involving rock-fragment components (RsRgRm) and the proportion of their related rocks at the sources shows:

(1) The high level of representation of metamorphic sources in the sands, with increases of RsRgRm%Rm means of 18%, 23.1% and 18.1% (Provinces A, B and C+D, respectively) with respect to the means of metamorphic source area distribution.
(2) The direct relationship of sedimentary lithics with the proportion of their sources, but always underrepresenting these sources. This loss of sedimentary source representation in the sands is manifested by a difference between the mean of surface occurrence of these sources and the RsRgRm%Rs mean of 21%, 17.5% and 10.7% in sands from Provinces A, B and C+D, respectively.
(3) The relative good fit of phaneritic rock fragments with respect to the proportions of plutonites at the source, in Provinces A and B, but underrepresenting these rocks in the sands of the lower course (Provinces C and D). This underrepresentation is manifested by a mean difference of 5.6% and 7.5% (Provinces B and C+D, respectively) between surface granitic occurrence and RsRgRm%Rg grains in the corresponding sands.

Tajo River sand composition is less mature than the composition of sand from several big rivers from Atlantic-type trailing-edge sands of the same tectonic setting (e.g., Potter, 1978a). This could be related to the fact that climatic interval along the Iberian passive margin mitigates maturation of sediments, in contrast to other Atlantic big rivers that are located in tropical climatic regimes. Thus, a tectonic classification of big rivers using sand composition must include the climatic setting at the drainage area.

The good correlation of Tajo River basin sand composition with source rocks and with the tectonic setting of source terranes is a result of the weathering-limited denudation regime prevalent within the Iberian Peninsula.

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