

THE RECYCLED OROGENIC SAND PROVENANCE FROM AN UPLIFTED THRUST BELT, BETIC CORDILLERA, SOUTHERN SPAIN

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ABSTRACT: The Betic Cordillera of southern Spain represents an uplifted foreland fold-thrust belt. Source rock types of the Betic Cordillera include metamorphic (mainly phyllite, schist, quartzite, and gneiss), sedimentary (siliciclastic and carbonate), volcanic (felsic to intermediate pyroclasts), and mantle-derived (peridotite, gabbro, serpentinite, and serpentine schist) rocks. The fluvial systems range that transect the Betic Cordillera are the major detrital source of sediment along the southern Spanish coast, supplying sand to beaches and offshore depositional systems in the Alboran Sea basin.

Three key sand petrofacies derived from the Betic mountain belt reflect the main clastic contribution of known source rocks. All the sands are quartzolithic, ranging from quartz-rich to lithic-rich.

Fluvial systems draining the Sierra de Los Filabres, the Sierra Nevada, the Sierra de Gador, and the Málaga Mountains, and their related beaches constitute a metamorphic-sedimenticlastic quartzolithic sand petrofacies ($Qm34 \pm 10$ $F4 \pm 3$ $Lt62 \pm 9$; $Lm72 \pm 14$ $Lv2 \pm 4$ $Ls26 \pm 13$), derived dominantly from the Nevado-Filábride, Alpujárride, and Maláguide complexes. This quartzolithic petrofacies extends from northeast of Almería to Torremolinos (southwest of Málaga), and northeast of Algeciras. Only one beach sand sample, east of Cabo de Gata, is volcanolithic. Volcanic detritus (mainly having felsitic textures) is derived from Miocene (15–7 Ma) pyroclastic sequences cropping out in the southeast of the chain.

This metamorphic-sedimenticlastic quartzolithic petrofacies changes in the coastal stretch from Torremolinos to Marbella, where drainage systems cut across the Serranía de Ronda. Here source rock types include peridotite, gabbro, and serpentinite of the Ronda Peridotite Massif, and metamorphic rocks of the Maláguide and Alpujárride units. The fluvial and beach sands of this area are quartzolithic ($Qm32 \pm 12$ $F10 \pm 3$ $Lt58 \pm 11$), and include abundant peridotite and serpentinite grains. The latter quartzolithic petrofacies changes abruptly from Algeciras to Cádiz, where the sand becomes quartz-rich ($Qm77 \pm 5$ $F4 \pm 2$ $Lt19 \pm 4$). This sand petrofacies is derived predominantly from recycling of sedimentary sequences, mainly the quartzarenite turbidite units of the Gibraltar Arc (the Algeciras Flysch). This petrofacies is characterized by higher proportion of quartz grains and abundant sedimentary lithic fragments ($Lm1 \pm 3$ $Lv1 \pm 1$ $Ls98 \pm 3$).

The three onshore petrofacies plot in the recycled-orogen provenance compositional field and the lithic to transitional to quartzose recycled subfields of Dickinson (1985). They vary from lithic, to transitional and quartzose depending on their source lithologies in the Betic foreland fold-thrust belt. These actualistic petrofacies best describe the nature and distribution of sand petrofacies derived from a collisional fold-thrust belt where primary and recycled source rocks are interfingered.

Deep-marine turbidites of the Alboran Basin have basinwide quartzolithic sands having close compositional relations with Betic Cordillera onshore sand petrofacies. Comparison of detrital modes

from mainland to deep-marine environments provides a suitable basis for interpreting the Miocene to Pleistocene sand dispersal history in the Alboran Basin. These modern quartzolithic petrofacies are used to interpret analogous ancient collisional sandstone petrofacies of the Alpine orogenic belt of the western-central Mediterranean region and of other collisional orogenic systems, as a broader point of view.

INTRODUCTION

The Betic Cordillera is an uplifted thrust belt, consisting of several thrust units and having a wide spectrum of source rock types, including metamorphic (low- to high-grade), mantle-exhumed rocks (peridotite complex), sedimentary (carbonate, siliciclastic, and evaporite), and volcanic rocks. These source rocks supply large amounts of detritus to the coastal and marine environments of the Alboran Sea.

The Alboran Sea is a tectonically active, postcollisional basin, located in the broad region of deformation that marks the modern African and European plate boundary. This extensional basin is superimposed on the Alpine orogenic belt, and it is surrounded by the Betic and Rif mountain belts (Fig. 1).

The Alboran Basin has been intensely investigated, most recently by the Ocean Drilling Program (ODP) on Leg 161 (Zahn et al. 1999). One purpose of ODP Leg 161 was to characterize and compare the depositional history of the Alboran and other sub-basins of the Western Mediterranean (Comas et al. 1996). Marsaglia et al. (1999) used samples from the Leg 161 cores to investigate the history of Miocene to Pleistocene detrital sedimentation in the Alboran Basin. One of their main conclusions was that the turbidite sands at Sites 976, 977, and 978 were derived from the Betic Cordillera of southern Spain.

The Betic Cordillera and the Alboran Basin represent a well known orogenic system of a collisional chain and the associate extensional basin, respectively. Actualistic studies on modern petrofacies in this area allows interpreting geotectonic provenance in analogous geologic settings. To better characterize the onshore dispersal pathways and the geographical distributions of modern sand petrofacies around the northern active flank of the Alboran Sea, we determined the detrital modes of sand samples from fluvial and beach environments of the Mediterranean and Atlantic sides of the Betic Cordillera, southern Spain. Another purpose of this study is to compare sand detrital modes collected from fluvial and coastal environments to data from sands recovered in deep-marine environments on ODP Leg 161, in an effort to clarify the source-to-basin pathways of sandy sediment in the northern Alboran Basin. The onshore and offshore compositional data sets form the basis of an actualistic model for interpreting the provenance of ancient sandstones deposited in sedimentary basins developed during the collisional evolution of the Mediterranean region (e.g., Schwab 1981; Valloni and Zuffa 1984; Critelli and Le Pera 1995, 1998).

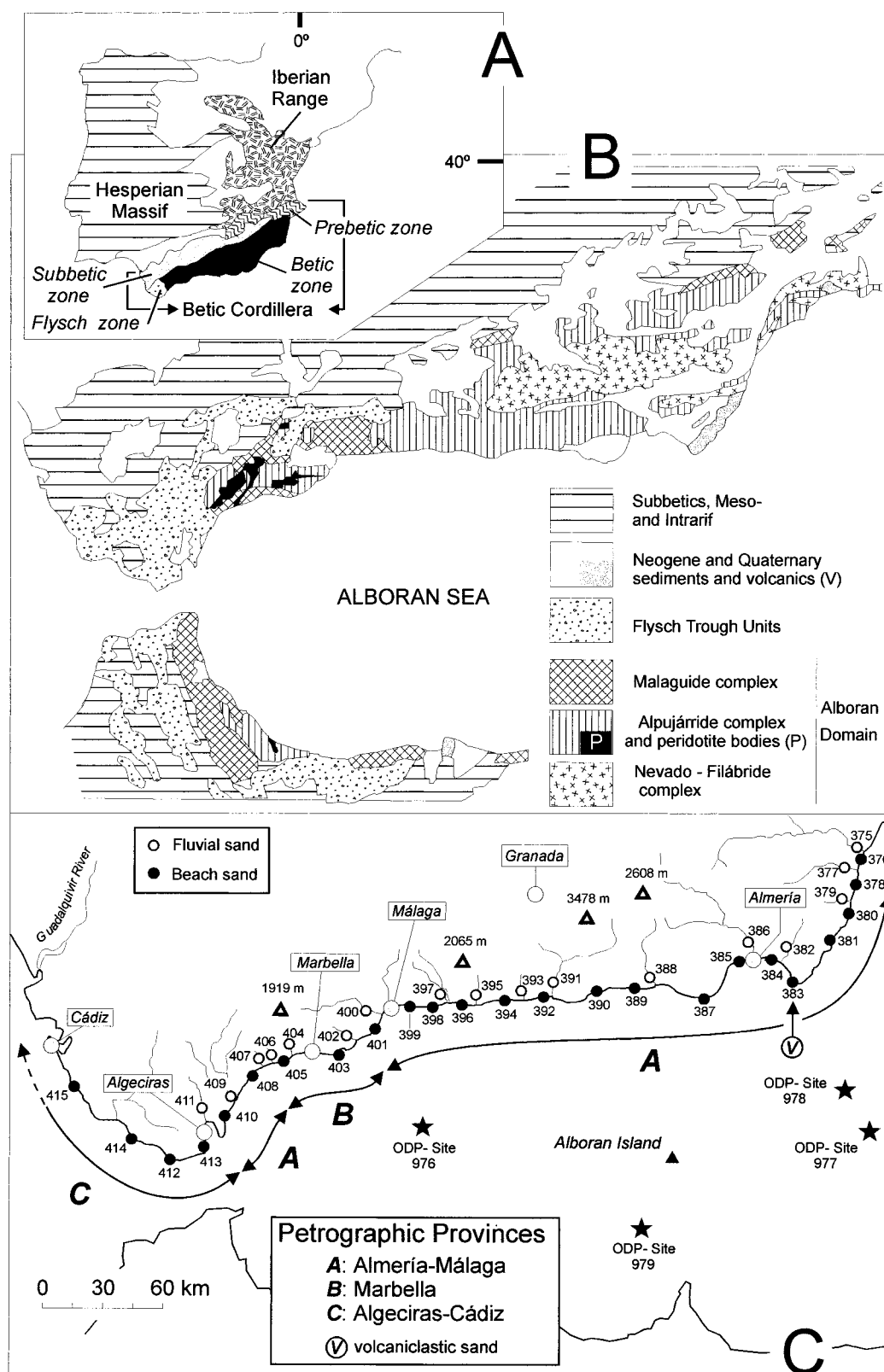


FIG. 1.—Geographic and geologic sketch map (after Balanyá et al. 1998) of the Mediterranean side of the Betic thrust belt. Location of analyzed modern sand samples is shown, as such as location of the ODP Sites 977–979 within the Alboran Sea.

TABLE 1.—Site location of sand samples used for the compositional study.

Sample	Environment	Site Location
375	Fluvial	Río Almanzora (c. 1 km from the mouth)
376	Beach	Puerto Rey (c. 5 km southwest from Río Almanzora river mouth)
377	Fluvial	Río de Aguas (c. 3 km from the mouth)
378	Beach	Pueblo Índao (c. 6 km southwest from Río de Aguas river mouth)
379	Fluvial	Río Carboneras (c. 1 km from the mouth)
380	Beach	Carboneras (La Puntica; c. 5 km southwest from Río Carboneras river mouth)
381	Beach	Las Negras
382	Fluvial	Río Morales (c. 3 km from the mouth)
383	Beach	Salinas del Cabo de Gata
384	Beach	El Alquídn
385	Beach	Punta del Río (Almería; c. 2 km west from the Río Andarax river mouth)
386	Fluvial	Río Andarax (Almería; c. 3 km from the mouth)
387	Beach	Punta Sabinar
388	Fluvial	Río Adra (c. 2 km from the mouth)
389	Beach	Adra (c. 2 km west from Río Adra river mouth)
390	Beach	Castillo de Baños
391	Fluvial	Río Guadalfeo (c. 4 km from the mouth)
392	Beach	La Caleta (c. 3 km west from Río Guadalfeo river mouth)
393	Fluvial	Río Verde (c. 2 km from the mouth)
394	Beach	Punta de la Mona (c. 4 km west from Río Verde river mouth)
395	Fluvial	Río Torrox (c. 2 km from the mouth)
396	Beach	Lagos (c. 5 km west from Río Torrox river mouth)
397	Fluvial	Río Vélez (c. 2 km from the mouth)
398	Beach	Almayate (c. 4 km west from the Río Vélez river mouth)
399	Beach	La Cala del Moral (east of Málaga)
400	Fluvial	Río Guadalhorce (c. 3 km from the mouth; Málaga)
401	Beach	Lido (c. 4 km southwest from the Río Guadalhorce river mouth)
402	Fluvial	Río Fuengirola (c. 2 km from the mouth)
403	Beach	Torre Calahonda (c. 8 km southwest from the Río Fuengirola river mouth)
404	Fluvial	Río Verde de Marbella (c. 2 km from the mouth)
405	Beach	San Pedro de Alcántara (c. 3 km southwest from the Río Verde de Marbella)
406	Fluvial	Río Guadalmína (c. 3 km from the mouth)
407	Fluvial	Río Guadalmansa (c. 2 km from the mouth)
408	Beach	Punta del Castor. Estepona (c. 2 km southwest from the Río Guadalmansa)
409	Fluvial	Río Guadiaro (c. 4 km from the mouth)
410	Beach	La Atunara (c. 5 km southwest from the Río Guadiaro)
411	Fluvial	Río Guadarranque (c. 10 km from the mouth)
412	Beach	Punta de Tarifa
413	Beach	Getares
414	Beach	Zahara de Los Atunes
415	Beach	La Barrosa (south of Sancti Petri)

taceous to lower Miocene quartzose turbidite sequences (Aljibe and Algeciras Units, and unnamed Cretaceous sandstone) and clays (Gutiérrez-Mas et al. 1991).

The Internal Domain (Alboran Domain or Betic Zone) includes stacked thrust sheets composed of metasedimentary and sedimentary rocks of Paleozoic to Tertiary age (Fig. 1A, B). The Internal Domain is subdivided into the Nevado/Filábride Complex and the Higher Betic Nappe. The latter is exposed only in the eroded core of the Betic ranges. The Nevado-Filábride Complex includes Paleozoic garnet-bearing and chloritoid-garnet mica schists and quartzite, local cordierite, andalusite, sillimanite, and garnet gneiss (Lundeen 1978), Paleozoic to Triassic mica schist, marble, calc-schist, albite-epidote amphibolite, metavolcanic and serpentinite rocks, and Triassic calcareous breccia and dolostone (Weijermars 1991, and references cited therein).

The Nevado-Filábride Complex is overlain by the Higher Betic Nappe. The latter consists of two main thin thrust sheets, the Alpujárride and Málaga complexes. In a few locations Triassic metasedimentary terranes (Almágride Complex) separate the Nevado-Filábride Complex from the Alpujárride Complex.

The Alpujárride Complex includes Paleozoic (pre-Silurian?) quartzite, mica schist, garnet-bearing schist, epidote schist, and marble; Permian-to-Triassic phyllite, quartzite, and graphite-bearing and garnet-bearing schist with interbedded marble and metabasalt; and Triassic gypsum, limestone, and dolostone. The Alpujárride Complex, in the westernmost part of the Betic zone, includes the Ronda Peridotite Complex, the world's largest exposure of upper-mantle rocks (~ 300 km²). The Ronda Complex includes peridotite, olivine gabbro, and spinel or garnet pyroxenite (Dickey 1970) that has been minimally altered by serpentinization (Lundeen 1978; Weijermars 1991, and references cited therein).

The Maláguide Complex consists of unmetamorphosed to very low-grade metamorphic carbonate rocks, gypsum, chert, sandstone, shale, and conglomerate, ranging in age from Silurian to early Miocene.

The tectonic units of the Higher Betic Nappe are unconformably covered by early Miocene to Quaternary clastic, carbonate, and evaporite rocks.

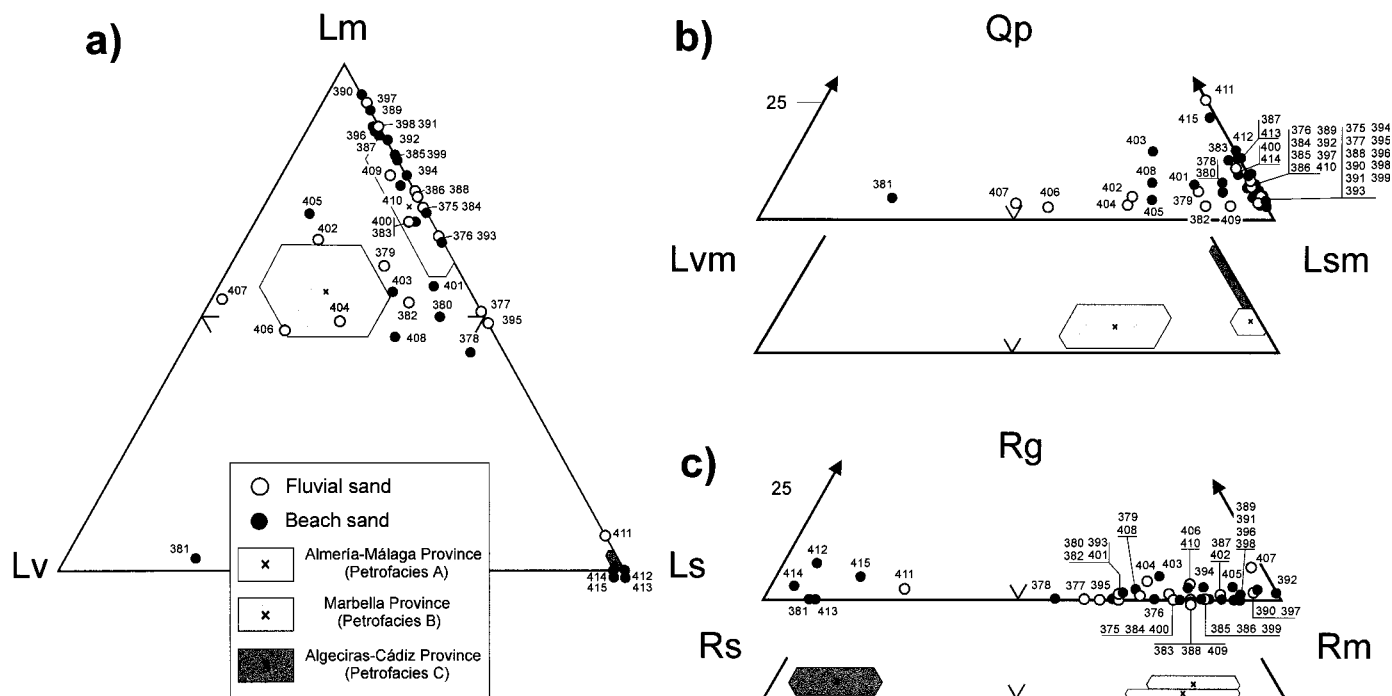


FIG. 3.—LmLvLs (a), QpLvmLsm (b), and RgRsRm (c) ternary plots of the modern fluvial and beach sand samples of the coastal side of the Betic Cordillera. Polygons are one standard deviation on either side of the mean.

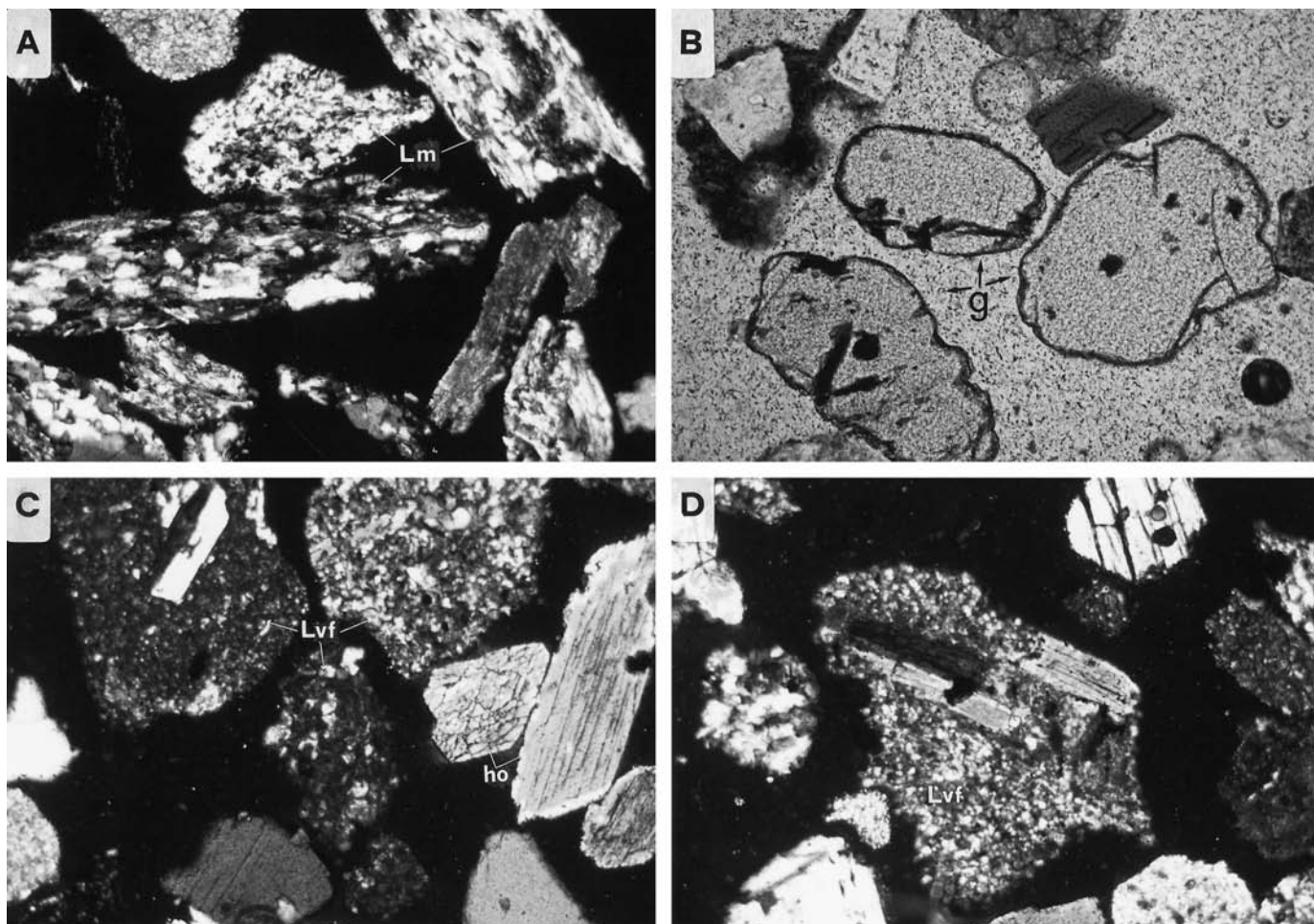


FIG. 4.—Photomicrographs of diagnostic grains for the modern fluvial and beach sand petrofacies of the coastal side of the Betic Cordillera. **A, B** Phyllite grains (Lm) and garnet grains from the metamorphic-sedimenticlastic petrofacies (Almería-Málaga Province). **C, D** Felsitic volcanic lithic fragments (Lv) and single brown hornblende (ho) crystals from the volcaniclastic sand petrofacies (Las Negras beach). **E, F** Phaneritic (Rp) and aphanitic (Lp) peridotite rock fragments with pyroxene (px) and amphibole (am) crystals from the ultramaficlastic petrofacies (Marbella Province). **G, H** Multicyclic quartz (q) grains with inherited overgrowths and siliciclastic sedimentary lithic fragments (Lss, quartzsiltstone) from the quartzose petrofacies (Algeciras-Cádiz Province). A, C-H = crossed nicols; B = plane-polarized light. Field size of photomicrograph: 1×0.7 mm.

Local outcrops of Miocene (15 to 7 Ma) calcalkaline (andesite to rhyolite) volcanic and volcaniclastic rocks occur along the coast from Cabo de Gata to Carboneras (Fig. 1; Weijermars 1991, and references cited therein).

METHODS

Forty-one sand samples were collected from fluvial and coastal environments (17 fluvial and 24 beach samples; Table 1), covering an area of more than 400 km in length (Fig. 1C). The 17 fluvial samples were collected from the active main channel and bars in the inner reaches of the channels. Beach sands were collected from high-tide berms at 24 localities (Table 1); each beach sand sample was collected 2000–8000 m southward of the corresponding river mouth (Fig. 1C).

All sand samples were washed using H_2O_2 to remove organic matter, air dried, and sieved (using 1-phi intervals). The 0.25–0.50 mm size fraction was used to prepare thin sections, which were etched with HF and stained by immersion in sodium cobaltinitrite solution to allow the identification of feldspars grains. Alizarine and potassium Fe-cyanide were also used for identification of carbonate grains. Three hundred points were counted on each thin section using the Gazzi-Dickinson method (Ingersoll et al. 1984). Point-count raw results and recalculated modal results are available in JSR's digital archives (see Acknowledgments).

RESULTS

Principal Compositional Groupings

We use detrital modes (expressed by suite means and standard deviation fields) to determine compositional variability of local drainage patterns, and the influence of source rock type on local coastal drainages and on shoreline and nearshore sand composition. The sand samples are poorly to well sorted and consist of coarse- to medium-size sand grains that are angular to rounded. All of the sand samples are quartzolithic (grand mean Qm39 F5 Lt56), ranging from highly quartzose to lithic rich (Fig. 2). Monocrystalline quartz ranges from 11% to 85% (QmFLt%Qm), and lithic grains range from 13% to 79% (QmFLt%Lt), whereas feldspars are only a minor component. Lithic fragment types are diverse, and include all source rocks of the southern flank of the Betic Cordillera: sedimentary (both siliciclastic and carbonate), metamorphic (low- to medium-grade), volcanic, and mantle-derived (peridotite, gabbro, serpentinite) rocks.

Dense minerals range from 0 to 23% of the counted grain totals. Several species were recognized during modal analysis. Garnet and opaque minerals are present in most of the samples. Of special note is the presence of abundant amphibole (tremolite and other amphiboles), pyroxene, and garnet in the samples taken along the coast of Málaga (samples 402 to 408).

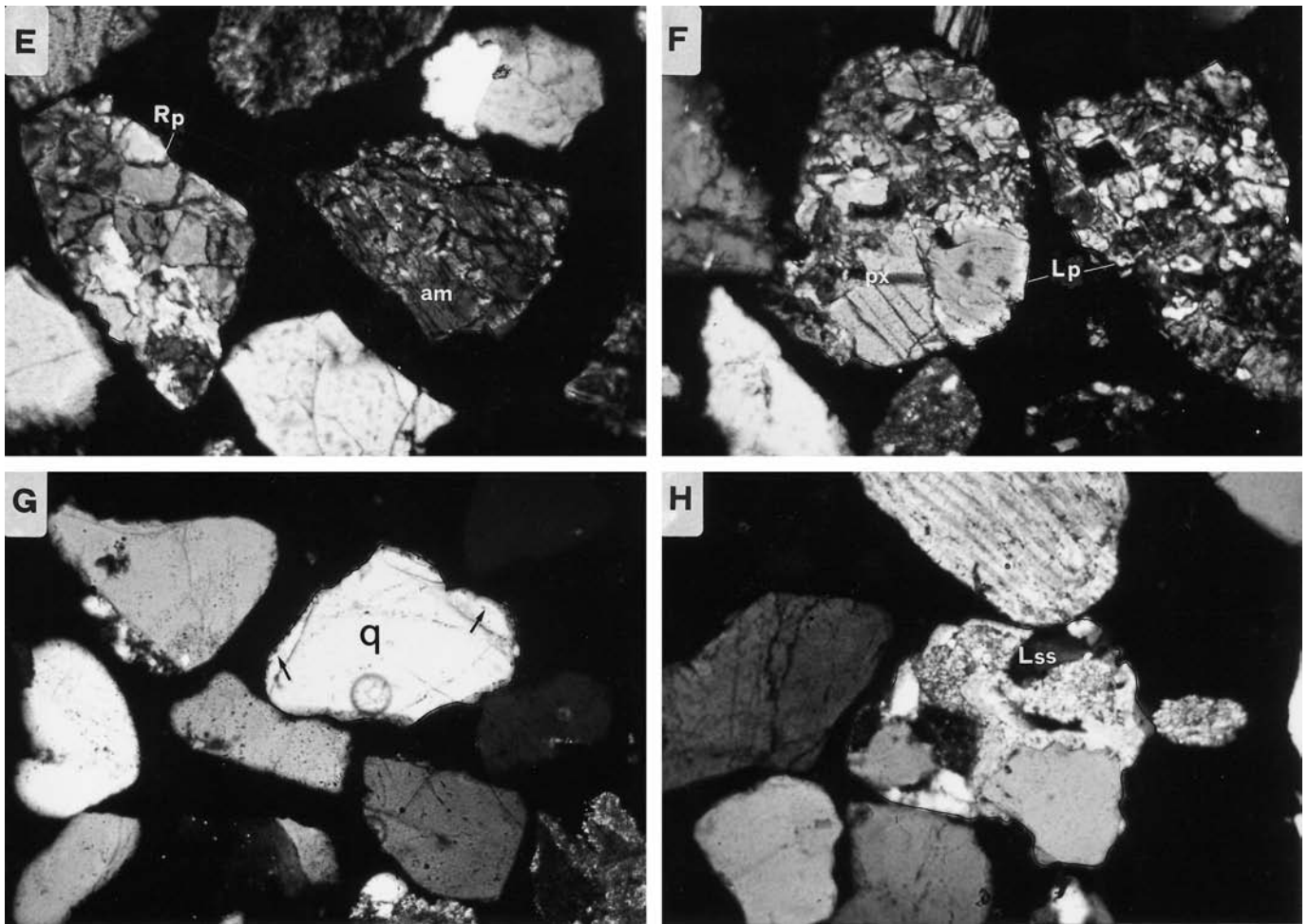


FIG. 4.—Continued

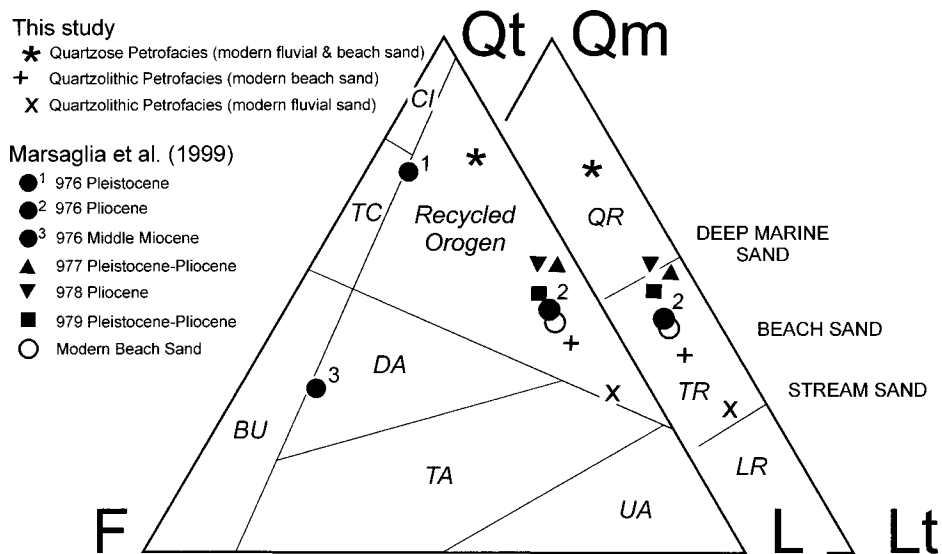


FIG. 5.—Mean sand compositions for the three modern onshore (fluvial and beach environments) sand petrofacies of the Betic coast, and for the Sites 976, 977, 978, and 979 and modern beach sand samples studied in Marsaglia et al. (1999) plotted on QmFLt and QtFL ternary diagrams with superimposed provenance fields of Dickinson (1985) (CI = craton interior; TC = transitional continent; BU = basement uplift; DA = dissected arc; TA = transitional arc; UA = undissected arc; QR = quartzose recycling; TR = transitional recycling; LR = lithic recycling).

Petrofacies Characteristics

The fluvial and beach sands of the Betic Cordillera are subdivided into three distinctive petrofacies based on visual inspection of the data. These three compositional groupings (Figs. 2, 3) correspond with the physiographic provinces of the Sierra de los Filabres, Sierra Nevada, and Málaga Mountains, here named Almería–Málaga Province (metamorphic–sedimenticlastic quartzolitic petrofacies), the Serranía de Ronda, named Marbella Province (ultramaficlastic quartzolitic petrofacies), and the southwestern end of the Betic coast, named the Algeciras–Cádiz Province (quartzose petrofacies). Only one sand sample (381) is volcanoclastic (Cabo de Gata–Carboneras province), and it will be described without formal definition of petrographic province.

Metamorphic–Sedimenticlastic Quartzolitic Petrofacies (Almería–Málaga Province).—This quartzolitic petrofacies corresponds to the fluvial systems draining the Sierra de los Filabres, the Sierra Nevada, and part of the Málaga Mountains, and their related coastal system. This petrofacies extends from the northeastern coast of Almería to Málaga (samples from 375 to 401; except the volcanoclastic sand sample 381), and eastern coast of Algeciras (samples 409 and 410). Sand of this petrofacies has abundant lithic grains and quartz ($Qm34 \pm 10$ $F4 \pm 3$ $Lt62 \pm 9$; Fig. 2), and feldspar is minor and dominantly plagioclase. Aphanitic lithic fragments ($Lm72 \pm 14$ $Lv2 \pm 4$ $Ls26 \pm 13$; Fig. 3) include abundant metasedimentary (phyllite, schist, minor quartzite, and fine-grained gneiss; Fig. 4A) and sedimentary (dolostone and limestone grains, siltstone, and fine-grained sandstone) grains. Only few samples (378, 379, 380, 382, and 383), located in the northeastern coast of Almería, also contain volcanic lithic fragments. These grains dominantly display a felsitic texture and were derived from the Miocene volcanic sequence cropping out at Cabo de Gata.

The abundant metasedimentary and sedimentary lithic fragments in this petrofacies are derived from the Nevado–Filábride, Alpujárride, and Málagaide Complexes, and Neogene sedimentary sequences. In particular, the metasedimentary lithic fragments, represented by phyllite, mica schist, graphitic schist, epidote schist, garnet-bearing schist, gneiss, and quartzite fragments, correspond with the Paleozoic metasedimentary successions of the Nevado–Filábride, Alpujárride, and Málagaide complexes. Gneissic fragments are derived from interbedded gneissic rocks of the Nevado–Filábride Complex, and from the Blanca Unit underlying the Ronda Peridotite (e.g., Lundeen 1978). These metasedimentary rocks contain abundant garnet, epidote, and other dense minerals typical of metamorphic rocks, which are abundant components of sand from their associated fluvial and beach systems (Fig. 4B).

Serpentine and serpentinite schist also are present, particularly in two samples from the southern coast of Málaga and related fluvial course (samples 400 and 401). This river cuts across the Málagaide and Alpujárride Complexes and the Ronda Peridotite Complex, the latter representing the key source for these ultramafic lithic grains.

Volcanoclastic Sand Petrofacies.—Only one sample, from Las Negras beach, is volcanoclastic. In addition to volcanic lithic fragments, it contains fragments of detrital carbonate (sample 381). The volcanic lithic fragments that dominate this sample ($LmLvLs$ 75% Lv) exhibit mainly felsitic granular to felsitic seriate textures (Fig. 4C, D). Hornblende crystals are also abundant (Fig. 4C), and sanidine and sodic to intermediate zoned plagioclase are present. The abundance of felsitic lithic fragments, in combination with the presence of hornblende and sanidine crystals, suggests a dominantly dacitic to rhyodacitic volcanic source. The carbonate fragments in this sand, are mainly recycled from mid-Late Tortonian sedimentary sequences that partly cover the volcanic sequence.

Ultramaficlastic Quartzolitic Petrofacies (Marbella Province).—This petrofacies corresponds to the four main fluvial systems draining the Serranía de Ronda and their relative river mouths, extending from Torremolinos to the western coast of Marbella (samples from 402 to 408; Table 1; Fig. 1). These quartzolitic sands ($Qm32 \pm 12$ $F10 \pm 3$ $Lt58 \pm 11$; Fig. 2)

have high percentages of serpentinite lithic fragments exhibiting cellular texture, fine-grained peridotite lithic fragments, and minor serpentinite schist fragments (Fig. 4E, F). More frequently, peridotite fragments occur as coarse-grained (phaneritic) fragments of amphibole, pyroxene, and rare plagioclase (Fig. 4E). Olivine crystals are apparently not preserved within the fragments. The sand samples also include abundant fragments of phyllite, schist, and fine-grained gneiss, whereas sedimentary lithic fragments are minor.

A remarkable feature of this petrofacies is the abundance of ultramafic rock fragments such as peridotite and serpentinite, and diagnostic ultramafic minerals such as pyroxene, amphibole, and serpentine. The Ronda Complex is the source terrane of the ultramafic debris in this petrofacies. Particularly, sand from the Guadalmina (sample 406) and Guadalmansa (sample 407) rivers has a total ultramafic contribution of over 50% of the counted grains (this ultramafic total is the sum of serpentinite, peridotite, and serpentinite schist lithic fragments, single mafic dense minerals, and plagioclase and dense minerals in coarse-grained peridotite and gabbro rock fragments). However, metasedimentary rocks in the other tectonic units also contribute significantly to the sand population of both the rivers and beaches.

Quartzose Petrofacies (Algeciras–Cádiz Province).—This petrofacies ($Qm77 \pm 5$ $F4 \pm 2$ $Lt19 \pm 4$; Fig. 2) corresponds with the coastal system that lies between Algeciras and Cádiz. The quartz content of these samples is high, ranging from 71% to 85% ($QmFLt\%Qm$). Feldspar is minor, and lithic fragments include dominantly siliciclastic and carbonate sedimentary fragments. Single quartz grains are well-rounded, occasionally exhibiting overgrowths (Fig. 4G), consistent with a recycled origin. Sedimentary lithic fragments include quartz siltstone, and fine-grained quartzarenite (Fig. 4H), in addition to abundant limestone and minor dolostone fragments. The abundant recycled quartz grains and fragments of quartzose sandstone and siltstone are derived from the flysch terranes of the Gibraltar Arc, which include dominantly Cretaceous to lower Miocene quartzarenite turbiditic sequences (Cretaceous flysch; Aljibe and Algeciras Units; Gutierrez-Mas et al. 1991). Limestone and dolostone grains document provenance from Triassic to Cretaceous units of the Subbetic Zone (Gutierrez-Mas et al. 1991).

DISCUSSION

The Recycled-Orogen Provenance Sand Suite

Quantitative detrital modes of sand and sandstones are used to help identify the tectonic setting of ancient basins, because of the close relationship between sand composition and the tectonic setting of the sand source terranes (e.g., Dickinson 1985, 1988; Valloni 1985). The typical sand suite derived from a fold–thrust belt, like the Betic Chain, is quartzolitic (e.g., Dickinson 1985; Schwab 1986; Critelli and Ingersoll 1994; Critelli and Le Pera 1995, 1998). Detrital modes of such sand(stone) suites were used by Dickinson et al. (1983) to define the recycled-orogen provenance field on a QFL diagram; this field can be further subdivided into a “quartzose,” “transitional,” and “lithic” subgroup on a $QmFLt$ ternary plot (Dickinson 1985). The quartz-rich quartzolitic sand suite is typically derived by mixing cratonic and fold–thrust belt sediment, or by recycling of previously accreted quartzose sediment sequences (Schwab 1986). The transitional and lithic quartzolitic sand suites are derived mainly from metasedimentary and sedimentary strata previously accreted within the fold–thrust belt, or from uplifted subduction complex terranes (Dickinson 1985; Le Pera and Critelli 1997; Garzanti et al. 1998; Garzanti et al. 2000).

The modern onshore sand of southern Spain is a typical example of an actualistic sand petrofacies that plots in the recycled-orogen provenance group, with distinctive compositions reflecting the “quartzose,” “transitional,” and “lithic” sands subgroups. Furthermore, this modern example provides information on the geographic distribution of petrofacies by depositional environment (e.g., stream, beach, and deep basinal settings), and allows direct correlation of sand composition to outcropping lithologies.

We first discuss the modern stream and beach sand detrital modes presented in this paper (from west to east) and then relate them to the detrital modes of deep-marine sand recovered during ODP drilling in the Alboran Basin.

Fluvial and Beach Sand Petrofacies

The quartzose sand petrofacies of the southern end of Spain (Algeciras–Cádiz Province) are derived by recycling of Cretaceous and Oligocene to Miocene (Aljibe and Algeciras units) quartzarenite turbiditic strata, and Mesozoic carbonate strata. The presence of multicyclic detritus is indicated by abundant well-rounded quartz grains, quartz grains with preserved rounded overgrowths, and fragments of carbonate-cemented quartzose siltstone and fine-grained quartzarenite. This quartzose petrofacies reflects a dominant derivation from Tertiary craton-derived clastic sequences deposited during early developmental stages of the Betic and Rif foreland basin system (e.g., Cazzola and Critelli 1987; Guerrero et al. 1993).

The Mediterranean coast of Spain is characterized by a large physiographic province associated with the Betic fold–thrust belt. The composition of sand derived from this province is typically “lithic to transitional” quartzolitic. The Betic coastal stretch from Almería to Algeciras includes two distinct quartzolitic petrofacies, a metamorphic–sedimenticlastic (Almería–Málaga Province) and an ultramaficlastic (Marbella Province). The metamorphic–sedimenticlastic quartzolitic petrofacies is derived from metasedimentary and sedimentary sequences of the stacked tectonostratigraphic terranes of the lesser and higher Betic units. The ultramaficlastic quartzolitic petrofacies of the Marbella Province is derived mainly from the Ronda Peridotite Complex, which supplies abundant peridotite, gabbro, and serpentinite detritus to the fluvial and coastal environment. These two onshore quartzolitic petrofacies essentially constitute the detrital supply from tectonostratigraphic terranes of the Betic fold–thrust belt.

The quartzolitic petrofacies derived erosion of the Betic fold–thrust belt thus reflects a recycled-orogen provenance. In the case of these petrofacies, it is possible to constrain the close relationship between the stacked source lithologies and their occurrence within the sand.

Alboran Basin Sand: Comparing Onshore and Offshore Sand Composition

Three of the sand-bearing sites drilled during ODP Leg 161 in the Alboran Basin contain sand likely derived from the coastal areas of Spain that were sampled in this study (Fig. 1). We discuss their detrital modes as determined previously (Latter 1998; Marsaglia et al. 1999) and compare them to the more extensive onshore data base collected for the present study.

The sandy sections at these sites range in age from Miocene to Pleistocene. The very fine- to fine-grained sand is present in isolated pods (burrow fills), and thin laminae to thin beds, some exhibiting scoured bases and normal grading. The sand was likely transported basinward via submarine-channel systems extending off the Betic coast. Once deposited by turbidity currents, the sediment may have been winnowed and reworked by bottom-current activity (Comas et al. 1996). Coarser-grained sand is limited to the few Miocene samples examined. The depositional settings for this lowstand material remain equivocal, but they are possibly marginal marine to nonmarine (Comas et al. 1996).

Several offshore petrofacies were defined by Marsaglia et al. (1999) in the sandy deposits cored at these ODP sites. They used the detrital modes of a small number (10) of beach sand samples to help clarify the Alboran Basin sand provenance. The offshore petrofacies correspond, to some degree, with the modern petrofacies defined in this study.

Here we compare these compositional groups on more general QtFL and QmFLt ternary plots because of slight differences in definition of lithic fragments between Marsaglia et al. (1999) and this study. For example, Marsaglia et al. (1999) treated the serpentinite-serpentinite as metamorphic

rock fragments, whereas in this study they were tallied with volcanic debris. Also there appear to be some differences in the proportions of metamorphic and sedimentary rock fragments in corresponding beach sand samples; these differences could be a product of category definitions and subtle textural variations in shale–slate–phyllite fragments as discussed in Dorsey (1988). Despite these differences in lithic-fragment categories, the grand QtFL and QmFLt means for both data sets are fairly similar (Fig. 5).

The onshore metamorphic–sedimenticlastic quartzose petrofacies corresponds with the composition of sand from the Pliocene to Pleistocene section at Site 977 and the Pliocene sections at 978 and 976. Based on submarine physiography and sparse beach sand compositions, Marsaglia et al. (1999) favored an Andarax River source via the Almería channel for this sand at Sites 977 and 978. The detailed beach and fluvial data set collected for this study also supports such a source.

Site 976 is situated south of Málaga, more proximal to the onshore areas with the ultramafic quartzolitic petrofacies and the quartzose petrofacies than 978 and 979. There is, however, no exact equivalent of the ultramafic quartzolitic petrofacies in the offshore sandy units. Only one offshore sample, the youngest Pliocene sandstone recovered at Site 976, contained a significant (5% of total grains counted) quantity of serpentinite. Other samples stratigraphically below this serpentinite-rich sample contained only traces of serpentinite. The upsection increase in serpentinite may be a function of the development of onshore drainage across increasingly larger areas of peridotite outcrop.

The onshore quartzose petrofacies is most similar in composition to the Pleistocene sand recovered at Site 976, but the offshore sand is much more enriched in feldspar (Fig. 5). Marsaglia et al. (1999) hypothesized a Gibraltar area source for this sand. These source supplies were transported eastward during periods of estuarine circulation generated by surface-water freshening during glacial minima. The beach and stream sand data collected in this study strengthen this argument.

One of the surprising results of the Marsaglia et al. (1999) study was the limited volcanic component in the deeper part of the Alboran Basin, where basin highs are generally thought to be volcanic in nature. In terms of modern outcrops, volcanic rocks are limited to the easternmost part of the Betic zone of southern Spain (Fig. 1B). These units produce sands that exhibit a variety of volcanic lithic textures as indicated by the mix of felsitic, microlitic, and lathwork textures shown by sample 381 in this study, and the vitric and crystal components in a beach sand sample examined by Marsaglia et al. (1999). The volcanic components in the three Miocene samples indicate altered vesicular vitric fragments at Site 976 and minor felsitic fragments at Site 977.

A fourth ODP site (979), drilled more proximal to the African margin, provides some additional information on the variability and controls of sand composition across the basin. The Pleistocene to Upper Pliocene sand deposited at Site 979 was generally more enriched in sedimentary lithic fragments than sand from the northern sites. This is not as we expected, in that onshore African outcrops are dominated by sedimentary units. Marsaglia et al. (1999) noted that there was some evidence to suggest an unroofing history of that margin, with older samples enriched in sedimentary fragments and younger sands tending to be more enriched in metamorphic lithic fragments. In addition, a few samples contained unaltered sand-size glass shards, produced during volcanic activity either on the African mainland or the nearby Alboran Ridge. Despite these variances in lithic types the overall proportion of QtFL components was very similar to those of the other sites from the northern part of the basin (Fig. 5).

Compositional Trends among Stream, Beach, and Basinal Sand Samples

As indicated on Figure 5, there are distinct compositional differences among offshore and onshore sand populations in the Betic province. On average, the stream sand samples are more lithic rich, and the beach sam-

ples more quartz rich. The deep marine sand samples are even more quartzose than even the beach samples. This facies-related compositional trend is similar to that documented in fluvial, beach, and turbidite facies of the Pennsylvanian Minturn Formation of Colorado (Kairo et al. 1993), of the Tyrrhenian (Le Pera and Critelli 1997) and Ionian margins of Calabria (Critelli and Le Pera 2001), and in southern California (Critelli et al. 1997). In general, the offshore sands are finer grained than their onshore counterparts, suggesting that some of the compositional shift to more quartzose sand in basinal settings could also be related to compositional fractionation by grain size. Thus, the onshore modern quartzose petrofacies sand exhibits a composition distinct from that of the possible offshore Pleistocene equivalents at Site 976 (Fig. 5). The latter are much more enriched in feldspar, and finer grained (Marsaglia et al. 1999). This trend could be explained by concentration of feldspar in the finer grain-size fraction (Odom et al. 1976). Climate, an important control on the survival of feldspar detritus in the rock record (e.g., Le Pera et al. 2001), could also have played a role in the preferential concentration of feldspar in the Pleistocene at Site 976. If sand delivery to this site was tied to glacial cycles as proposed by Marsaglia et al. (1999), then their higher feldspar content also could be climate related. Higher feldspar content could be linked to periods of less intense chemical weathering in the source area. The lesser quantity of serpentine in the offshore sections also could be a function of transport distance. The softer serpentine might break down and be preferentially concentrated in the silt size fraction.

CONCLUSIONS

This study of modern fluvial and coastal sands from the Betic Cordillera (southern Spain) shows how various types of petrofacies derived from a recycled-orogen system can be discriminated among the main structural domains of a chain.

Three onshore petrofacies have been recognized, and they plot in the recycled-orogen provenance compositional field and the lithic to transitional to quartzose recycled subfields of Dickinson (1985). They vary from lithic subfield, to transitional and quartzose subfields depending on their source rocks in the Betic foreland fold-thrust belt, where primary and recycled source rocks are interfingering.

The metamorphic-sedimentoclastic quartzolitic petrofacies (Almería-Málaga Province) consists mainly of sands with abundant lithic (metasedimentary and sedimentary) fragments and quartz grains (mean of Qm34F4L62 and Lm72Lv2Ls26). Sources for this petrofacies are the Paleozoic metasedimentary successions of the Nevado-Filábride, Alpujárride, and Málaga complexes, and the Neogene sedimentary sequence. This mixed metamorphic-sedimentoclastic petrographic province is the widest province developed on the Betic coast, running from the northeastern coast of Almería to Málaga. This petrofacies is also identified at the eastern coast of Algeciras (Fig. 1). A volcanoclastic sand petrofacies (Qm11F16L73) is developed locally in the Cabo de Gata area (Las Negras beach), and is derived from the erosion of Miocene calcalkaline volcanic sources.

The ultramaficlastic quartzolitic petrofacies (Marbella Province) is characterized by peridotite- and serpentinite-rich sand with abundant Ferromagnesian minerals (amphibole, pyroxene, and serpentine) (mean of Qm32F10L58 and Lm55Lv26Ls19). The spatial distribution of this petrofacies is from Fuengirola to Estepona localities, around Marbella, and reflects derivation mainly from mantle-derived sources (Ronda Peridotite Complex).

The quartzose petrofacies (Algeciras-Cádiz Province) sand (mean of Qm77F4L19) is sedimentoclastic in origin with a predominance of quartz siltstone, quartzarenite, limestone, and minor dolostone as the main sedimentary lithics (mean of Lm1Lv1Ls98). The dominant sources are the quartzose flysch units of the Gibraltar Arc, with minor contributions of the sedimentary sequence from the Subbetic Zone. This petrofacies appears in the Atlantic side of the Betic coast, between Algeciras and Cádiz. This

composition could represent the ultimate western Betic provenance before sedimentary processes of the Guadalquivir river mouth system control the coastal sediment dispersal.

The onshore petrofacies are closely correlative with turbidite sand petrofacies of the Alboran Basin. Detailing the geographic distribution of the onshore petrofacies provides a suitable basis for interpreting the Miocene to Pleistocene sand dispersal in the deep-marine Alboran Basin and unraveling the tectonic evolution of the Betic orogen. These modern quartzolitic petrofacies are used to interpret analogous ancient collisional sandstone petrofacies of the Alpine orogenic belt of the western-central Mediterranean region. In addition, future works in similar geotectonic situations will benefit by the use of defined orogenic petrofacies.

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