

## *Modern stream sands from compound crystalline sources: Composition and sand generation index*

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### ABSTRACT

Compositions of modern first-cycle sands derived from granitic and metamorphic terrains in the Spanish Central System have been analyzed in order to evaluate the contributions of different bedrock types. The results of this work indicate that sand composition normally does not permit quantitative statements concerning sourceland composition. This is due to the fact that each rock type has a different potential to generate sand, dependent on such properties as its mineralogy, average crystal size, and microfabric. We introduce the concept of sand generation index (SGI), which is a relative measure of the capacity of one bedrock type to generate sand with respect to another in a compound source area. SGI of granitoid is 14 to 20 times greater than SGI of slate-schist when these rock types appear in a dual crystalline source. In the case of a gneiss + slate-schist source rock association, the SGI of gneiss is about five times greater than the SGI of slate-schist, whereas the SGI of gneiss is similar to that of granitoid in case of a dual granitoid + gneiss source. Finally, our results show that quantitative estimates of source land composition based on QFR diagrams are hazardous if the concept of the SGI is disregarded.

### INTRODUCTION

As shown by Mann and Cavaroc (1973), Basu et al. (1975), Dickinson and Valloni (1980) and other workers, the study of modern sands provides for a better understanding of the influence of source area composition, tectonic setting, weathering, transport, and climate on final sand composition. An integration of the results obtained from such studies should yield a more accurate interpretation of provenance in ancient deposits. In order to infer provenance, modal compositions of sands are usually plotted on ternary diagrams, such as QFR, QFL, or  $Q_mFLt$ , subdivided into diagnostic compositional fields (e.g., Dickinson and Suczek, 1979; Pettijohn et al., 1987). However, current interpretation schemes often appear insufficient, inasmuch as they either are based on the assumption of source areas consisting of a single rock type (Folk, 1974; Pettijohn et al., 1987) or, at the other extreme, they concern the discrimination between major geotectonic settings (Dickinson, 1985; Valloni, 1985). Petrofacies of sands derived from wide drainage terrains with different source materials can be used as a valuable tool for the distinction of

major provenance categories. On the contrary, on a smaller scale lithological variability in the source area critically affects sand composition (Ingersoll, 1991). At present many studies address more local problems in provenance analysis (e.g., Arribas and Arribas, 1991), where interpretations based on continental-scale data (Dickinson et al., 1983) are of more limited value. Therefore, the necessity arises to search for diagnostic criteria that will improve provenance interpretations at a smaller scale.

Little work has been done on quantifying the relative contribution of various source-rock types in a given source area to sand populations derived from that source area. Mack (1981) analyzed the compositional characteristics of modern sands derived from a mixed metamorphic and sedimentary source terrain. The results obtained suggest that this kind of approach may constitute a promising field for future research. What is the composition of a sand released from a source area that consists of two or more lithologic types in known relative proportions? What is the capacity of a certain source rock type to produce sand with

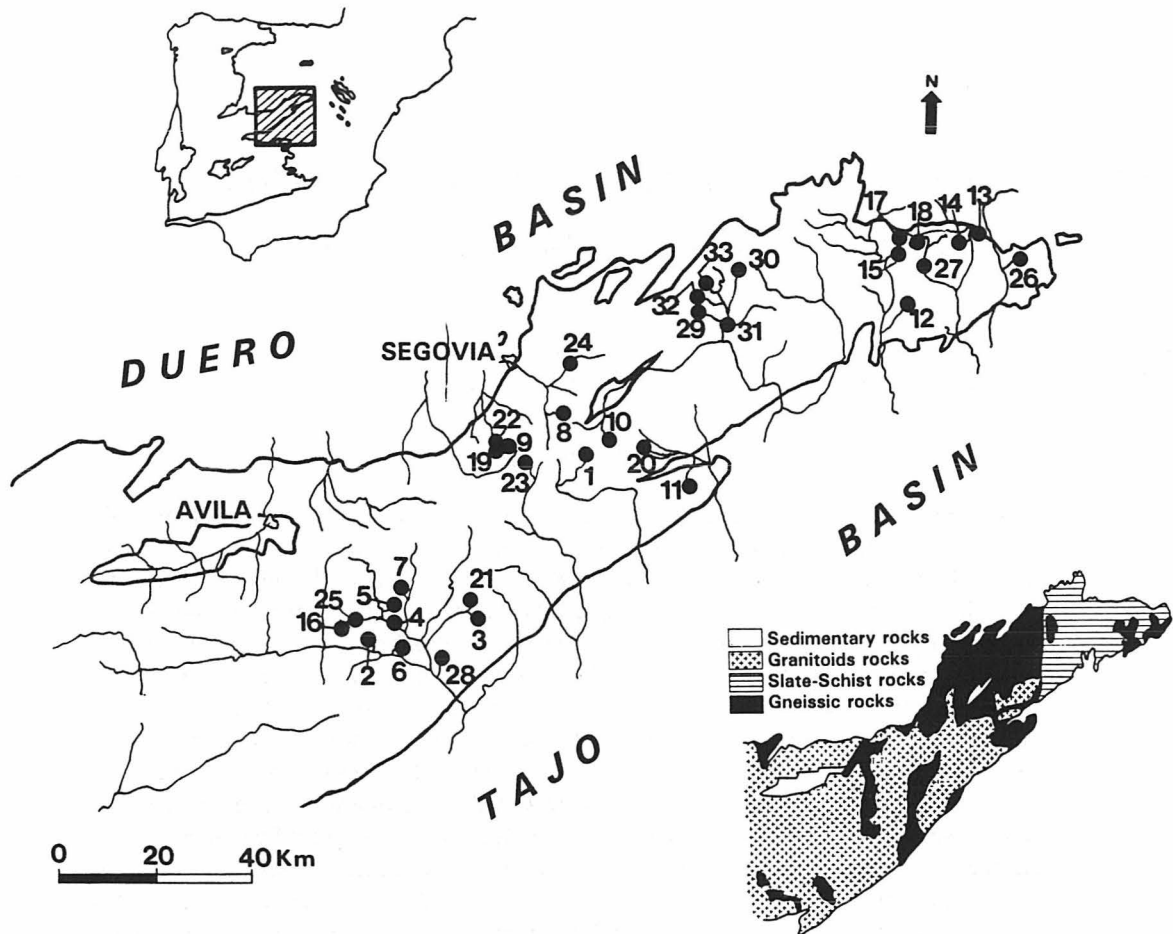


Figure 1. Location map of sampled drainage systems in the Spanish Central System. See Table 1 for identification and characterization of the individual drainage systems.

respect to another? To answer these questions, studies need to be attempted, particularly on modern sands, where source areas are well exposed and other provenance parameters (such as weathering, transport, climate) are known or can be quantitatively estimated.

The purpose of this study is to provide data concerning the composition of first-cycle sands derived from three different crystalline source rock associations, with particular emphasis on the influence of differing proportions of specific bedrock types in the source area on the final sand composition. The Spanish Central System has been selected because it provides exposures of various igneous and metamorphic rock types, as well as well-defined drainage basins with modern first-cycle stream sands. By using classical petrographic methods, the relative potential for sand generation of the different source rock types is quantitatively assessed.

#### CHARACTERISTICS OF THE SOURCE AREAS

The Central System is a northeast-southwest-trending mountain chain, about 400 km long, that is situated in the central part of the Iberian Peninsula (Fig. 1). The elevation increases toward

the southwest, reaching a maximum of 2,592 m (Pico Almanzor). Streams drain northward (Duero Basin) and southward (Tajo Basin). The Central System is a part of the Hesperian Massif (i.e., the southernmost portion of the European Hercynian Chain), uplifted during the Alpine Cycle, and consists largely of granitoids of late Hercynian age that intrude low- to high-rank (Precambrian and Paleozoic) metamorphic basement (Fig. 1). Granitoid lithologic varieties include biotite leucogranites, adamellites, pegmatitic to aplitic leucogranites, porphyritic adamellites, and granodiorites (Aparicio et al., 1975; Casillas and Peinado, 1988). The emplacement of the granitoids is thought to be related to late orogenic regional extension (Casquet et al., 1988). Metamorphic rocks include low-rank slates and schists (Lopez Ruiz et al., 1975), as well as gneisses (Aparicio and Galán, 1980; Navidad and Peinado, 1981; Villaseca, 1984). Composition and textures of sands derived from "simple" (i.e., single lithology) sources in the same area have been studied by Tortosa et al. (1989), Palomares et al. (1990) and Tortosa et al. (1991). The present climate in the Central System is semiarid, with mean annual precipitation ranging from 500 to 1,500 mm and mean annual temperatures ranging between 6° and 14°C.

TABLE 1. GENERAL DATA CONCERNING DRAINAGE SYSTEMS CONSIDERED IN THIS STUDY

Drainage Area	Lithology	Number of Samples	Surface Area (km <sup>2</sup> )	Maximum Length (km)	Relief Ratio*	Altitude (max.-min.) (m)
1 La Pedriza	Granitoid (Gr)	4	8.75	4.47	0.22	2,015–1,030
2 Jomillo	Granitoid (Gr)	1	0.15	0.70	0.10	690–620
3 Sobaquillo	Granitoid (Gr)	1	0.20	0.75	0.30	1,090–860
4 Fraile	Granitoid (Gr)	2	4.40	3.85	0.11	1,178–750
5 Enebrovilla	Granitoid (Gr)	4	3.85	3.15	0.10	1,071–720
6 Rosados	Granitoid (Gr)	2	0.75	0.90	0.16	831–685
7 Quintanar	Granitoid (Gr)	3	1.65	1.90	0.14	1,030–760
8 Valdeclemente	Granitoid (Gr)	1	2.06	3.50	0.27	2,182–1,220
9 Mujer Muerta	Gneiss (Gn)	4	5.60	3.60	0.24	2,196–1,320
10 Purgatorio	Gneiss (Gn)	2	1.15	1.50	0.21	1,610–1,290
11 San Pedro	Gneiss (Gn)	2	1.40	2.65	0.19	1,422–910
12 Prado Redondo	Gneiss (Gn)	2	1.00	1.45	0.07	1,100–990
13 Valdecanal	Slate-schist (Sl-Sc)	3	0.70	1.27	0.13	1,280–1,110
14 Retuerta	Slate-schist (Sl-Sc)	3	2.40	2.25	0.14	1,449–1,130
15 Morequero	Slate-schist (Sl-Sc)	2	0.90	1.50	0.22	1,589–1,260
16 Pajares	Slate-schist (Sl-Sc)	1	2.81	2.00	0.11	1,320–1,100
17 Pelagallinas	Slate-schist (Sl-Sc)	2	29.00	14.50	0.05	1,852–1,125
18 Cristóbal 1	Slate-schist (Sl-Sc)	2	6.12	5.90	0.09	1,821–1,300
19 Peña Hombre	Gr + Gn	5	3.95	3.10	0.23	2,003–1,290
20 Carpintera	Gr + Gn	4	4.92	7.00	0.08	1,460–895
21 Puebla	Gr + Gn	1	8.53	4.35	0.08	1,178–810
22 Milanillos	Gr + Gn	6	11.62	6.25	0.17	2,196–1,150
23 Infierno	Gr + Gn	6	2.09	2.25	0.32	2,009–1,290
24 Cambrones	Gr + Gn	9	48.00	12.50	0.07	2,078–1,120
25 Pizarra	Gr + Sl-Sc	6	20.96	7.75	0.07	1,320–730
26 Chorrón	Gn + Sl-Sc	3	1.71	2.00	0.16	1,408–1,090
27 Cristóbal 2	Gn + Sl-Sc	5	47.27	13.90	0.05	1,821–1,050
28 Lorenzo	Gn + Sl-Sc	1	1.81	2.40	0.11	811–540
29 Cigüeñuela	Gn + Sl-Sc	1	21.21	8.10	0.10	1,854–1,030
30 Xalle	Gn + Sl-Sc	2	12.02	5.15	0.15	1,834–1,050
31 Manadero	Gn + Sl-Sc	8	79.36	13.85	0.08	2,045–960
32 Solana	Gn + Sl-Sc	1	10.71	4.55	0.14	1,833–1,190
33 Dehesa	Gn + Sl-Sc	2	6.70	3.90	0.16	1,833–1,230

\*Relief (maximum-minimum elevations) divided by maximum length.

Accordingly, both mechanical and chemical weathering are moderate (Wilson, 1969).

## METHODS

For a quantitative assessment of the effects of a "compound" (i.e. mixed lithology) source on sand composition, the detrital modes of sands derived from simple sources were first analyzed. The source rock types present in the Central System have been grouped into three categories: granitoids, gneisses, and slate and schists. Sampling was performed on 33 modern drainage systems (Fig. 1). Two types of systems are distinguished, according to bedrock lithology at the source (Table 1): (1) Drainage systems with simple crystalline sources (constituted by granitoids, gneisses, or slate-schists). The area of the drainage basins ranges from 0.1 to 30 km<sup>2</sup>. They are between 700 to 2,200 m above sea level. First- or second-order streams, with lengths between 0.7 and 15 km and relief ratios ranging from 0.07 to 0.30, are typical.

(2) Drainage systems with dual crystalline sources (constituted by an association of granitoid + gneiss, granitoid + slate-schist, or gneiss + slate-schist). Drainage areas are between 2 and 80 km<sup>2</sup> and elevations between 800 and 2,200 m above sea level. Relief is moderate, with ratios ranging from 0.05 to 0.32. Streams are of first- to sixth-order, with lengths ranging from 2 to 14 km. In the case of the samples derived from this type of drainage areas, relative proportions of the individual lithologies in a given source area have been quantified according to Mack (1981; our Fig. 2).

The stream sands studied are from 81 different sites. At several sites more than one sample has been taken in order to test the reproducibility of analytical results. To avoid contamination, subaqueous bars in the inner reaches of the stream channels were sampled. Forty-one sand samples were collected in 18 drainage systems from homogeneous source terrains (one lithology) and 60 sands were sampled in main channels and major tributaries of 15 systems from compound source terrains (Table 1). In the source

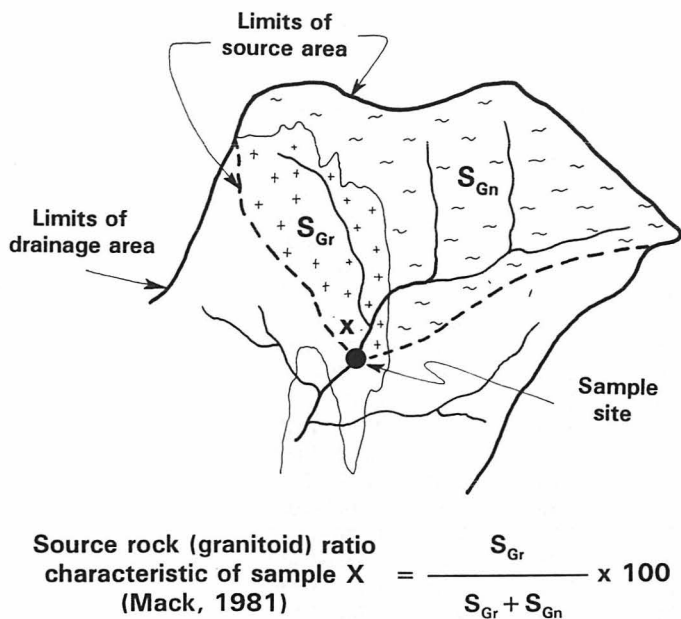


Figure 2. Sketch of a drainage system explaining the terminology used and showing the criterion adopted to establish the relative areal proportions of the bedrock types constituting a source terrain.  $S_{Gr}$  and  $S_{Gn}$  refer to the outcrop area of granitoid and gneiss bedrock, respectively.

terrains of the latter, the relative abundance of the constituent bedrock types has a considerable range. To avoid size-composition effects, only the medium-sand fraction (0.25 to 0.5 mm) has been considered. This fraction was separated by dry sieving and cemented with epoxy resin for thin-section preparation. Four hundred points were counted per thin section (Chayes, 1956) and the data subsequently evaluated according to both the "traditional" and Gazzi-Dickinson (1966) criteria (see also Zuffa, 1980, 1985). The modal compositions listed in Table 2 have then been plotted in QFR diagrams.

## SANDS DERIVED FROM SIMPLE SOURCES

### Grain types

Monocrystalline quartz is the dominant quartz grain type in both sands derived from simple granitoid and gneissic sources (25% and 26%, respectively, cf. Table 2). By contrast, the  $Q_m/Q_p$  (monocrystalline quartz/polycrystalline quartz) ratio in sands proceeding from slate-schist sources is typically around 1. In sands from granitoid sources, the percentages of undulatory and nonundulatory monocrystalline quartz is similar, as outlined by Tortosa et al. (1991). Medium sand-sized polycrystalline quartz grains from granitoid and gneissic sources (abundance: 5 to 8%, respectively) consist of a few crystals, typically less than three, whereas polycrystalline quartz grains derived from slate-schists (4.6%) tend to contain more than three crystal units per grain. This is related to the original crystal size in the parent rocks.

K-Feldspar and plagioclase occur as idiomorphic and subidiomorphic grains, both twinned and untwinned. Sands derived

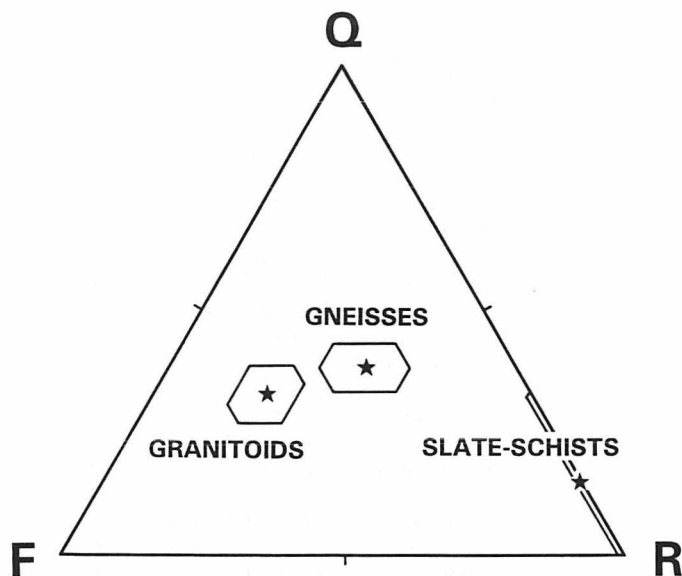


Figure 3. Mean compositions with standard deviations (1 SD) of modern medium-grained sands derived from simple sources (granitoids, gneisses, or slate-schists) in the Central System.

from granitoid sources contain the highest proportions of feldspar (46%), with a clear dominance of plagioclase ( $K/P = 0.8$ ). In sands released from gneissic sources feldspar content is less (27%), and K-feldspar (mainly microcline) prevails over plagioclase ( $K/P = 1.4$ ). The feldspar content in sands from slate-schist terrains is very low (0.6%); both plagioclase and K-feldspar are occasionally present.

Rock fragments in sands derived from granitoid as well as those from gneissic terrains (abundance, 19.6 and 34.7%, respectively) are composed of quartz-feldspar and quartz-feldspar-mica aggregates, typically with 3 to 5 crystals per grain in the former and 4 to 10 in the latter. Labile rock fragments (L-grains; Dickinson, 1970) are most frequent in sands released from slate-schist sources (58%). Muscovite, biotite, and chlorite also occur as single grains, but are quantitatively subordinate (generally <2%) in the medium sand fraction, as micas as individual grains tend to concentrate in the size fractions finer than 0.25 mm.

### Modal composition

The compositions of sands derived from slate-schist terrains plots within a narrow field parallel to the QR edge next to the R apex in the QFR diagram, with a mean of  $Q_{14}F_1R_{85}$  (Fig. 3). As shown by Tortosa et al. (1989), the relative proportions of quartz and rock fragments vary as a function of the original crystal size in the parent rock. Modal compositions of sands derived from granitoid and gneissic sources are similar, with means of  $Q_{33}F_{47}R_{20}$  and  $Q_{38}F_{27}R_{35}$ , respectively. The textural heterogeneity of gneisses (such as foliation, variable crystal size) results in

TABLE 2. MODAL COMPOSITIONS WITH STANDARD DEVIATION (1 SD) OF MEDIUM SANDS DERIVED FROM THE THREE TYPES OF COMPOUND SOURCES DISTINGUISHED\*

Mixing	Lithology Percentage	Qnu <sup>†</sup>	Qu <sup>§</sup>	Qp2-3**	Qp>3 <sup>‡</sup>	K-Fsp	Plag	Mica	Rc <sup>§§</sup>	L <sup>***</sup>	Q	F	R
Gr + Gn	100 Gr	11.0 ± 8.4	14.7 ± 8.5	5.0 ± 3.5	1.8 ± 1.9	21.2 ± 5.8	25.0 ± 7.2	1.4 ± 1.2	19.6 ± 5.6	0	32.7 ± 5.7	46.2 ± 8.4	19.6 ± 5.6
	30-50 Gn	21.3 ± 4.7	4.3 ± 1.0	5.4 ± 1.8	1.6 ± 1.8	19.0 ± 5.0	17.6 ± 7.3	3.3 ± 2.0	26.4 ± 7.3	0.2 ± 0.5	34.1 ± 4.0	38.2 ± 8.4	27.4 ± 7.4
	>50 Gn	18.6 ± 7.2	4.9 ± 1.9	7.3 ± 2.6	3.3 ± 2.2	21.0 ± 4.2	9.3 ± 3.0	3.2 ± 1.6	30.0 ± 5.3	1.6 ± 1.0	36.3 ± 5.7	31.0 ± 5.2	32.7 ± 6.2
	100 Gn	20.7 ± 6.5	5.6 ± 4.5	8.3 ± 2.7	4.1 ± 2.8	16.1 ± 5.6	11.1 ± 6.1	1.9 ± 1.0	34.7 ± 9.0	0	38.6 ± 6.7	27.2 ± 8.8	34.7 ± 9.0
Gr + Sl-Sc	100 Gr	11.0 ± 8.4	14.7 ± 8.5	5.0 ± 3.5	1.8 ± 1.9	21.2 ± 5.8	25.0 ± 7.2	1.4 ± 1.2	19.6 ± 5.6	0	32.7 ± 5.7	46.2 ± 8.4	19.6 ± 5.6
	10-30 Gr	15.9 ± 1.2	3.9 ± 2.1	4.5 ± 1.0	1.4 ± 0.9	19.4 ± 4.3	16.2 ± 3.3	3.6 ± 0.9	28.5 ± 4.4	4.5 ± 2.4	28.0 ± 3.0	36.4 ± 4.7	35.4 ± 4.2
	5 Gr	11.1	4.6	5.3	6.2	14.5	6.8	3.4	39.1	8.1	28.3	22.3	49.2
	100 Sl-Sc	4.9 ± 7.5	1.3 ± 1.7	1.9 ± 3.5	4.6 ± 5.2	0.5 ± 0.6	0.1 ± 0.2	0.4 ± 0.4	26.8 ± 10	58.1 ± 20.5	13.6 ± 18	0.6 ± 0.7	85.6 ± 18.7
Gn + Sl-Sc	100 Sl-Sc	4.9 ± 7.5	1.3 ± 1.7	1.9 ± 3.5	4.6 ± 5.2	0.5 ± 0.6	0.1 ± 0.2	0.4 ± 0.4	26.8 ± 10	58.1 ± 20.5	13.6 ± 18	0.6 ± 0.7	85.6 ± 18.7
	<40 Gn	5.6 ± 3.0	1.4 ± 0.9	4.2 ± 2.1	10.5 ± 4.7	1.8 ± 0.6	10.4 ± 3.5	2.9 ± 2.4	52.6 ± 4.5	9.7 ± 5.1	22.5 ± 7.1	12.5 ± 3.5	64.8 ± 4.5
	>40 Gn	21.7 ± 5.8	4.3 ± 2.1	8.5 ± 2.2	2.2 ± 1.0	9.1 ± 5.1	11.2 ± 3.5	3.3 ± 1.5	37.2 ± 5.2	2.3 ± 1.2	38.6 ± 7.0	20.2 ± 4.7	40.4 ± 5.8
	100 Gn	20.7 ± 6.5	5.4 ± 4.5	8.3 ± 2.7	4.1 ± 2.8	16.1 ± 5.6	11.1 ± 6.1	1.9 ± 1.0	34.7 ± 9.0	0	38.6 ± 6.7	27.2 ± 8.8	34.7 ± 9.0

\*Data from sands derived from simple sources (100% granitoid, 100% gneiss, or 100% slate-schist) are included to facilitate compositional trend analysis.

<sup>†</sup>Nonundulatory monocrystalline quartz.

<sup>§</sup>Undulatory monocrystalline quartz.

\*\*Polycrystalline quartz with 2 or 3 crystal units/grain.

<sup>‡</sup>Polycrystalline quartz with more than 3 units/grain.

<sup>§§</sup>Nonlabile rock fragments.

<sup>\*\*\*</sup>Labile rock fragments.

greater quantities of rock fragments in their weathered products as compared to granitoid-derived sands (Tortosa et al., 1989). The detrital mode of the sands derived from granitoid sources compares well with that of sands derived from similar source rocks under semiarid climatic conditions (Basu, 1976).

## SANDS DERIVED FROM DUAL SOURCES

### *Granitoid + gneiss (Gr + Gn)-derived sands*

The principal tendencies in compositional variation between sands derived from mixed sources are illustrated in Figures 4-6.

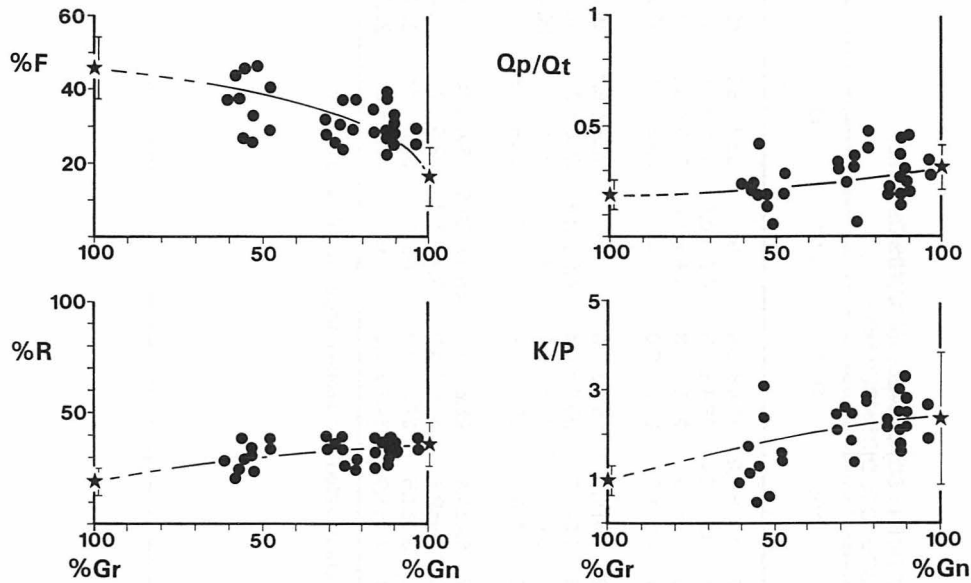


Figure 4. Compositional characteristics of mixed (granitoid + gneiss) derived sands versus percentage outcrop area of gneissic bedrock in the source terrain. Stars represent the mean compositions (with standard deviations) of sands derived from a 100% granitoid (Gr) source terrain and from a 100% gneissic (Gn) source. Qt = total quartz; Qp = polycrystalline quartz; F = total feldspar; K = K-feldspar; P = plagioclase; R = total rock fragments.

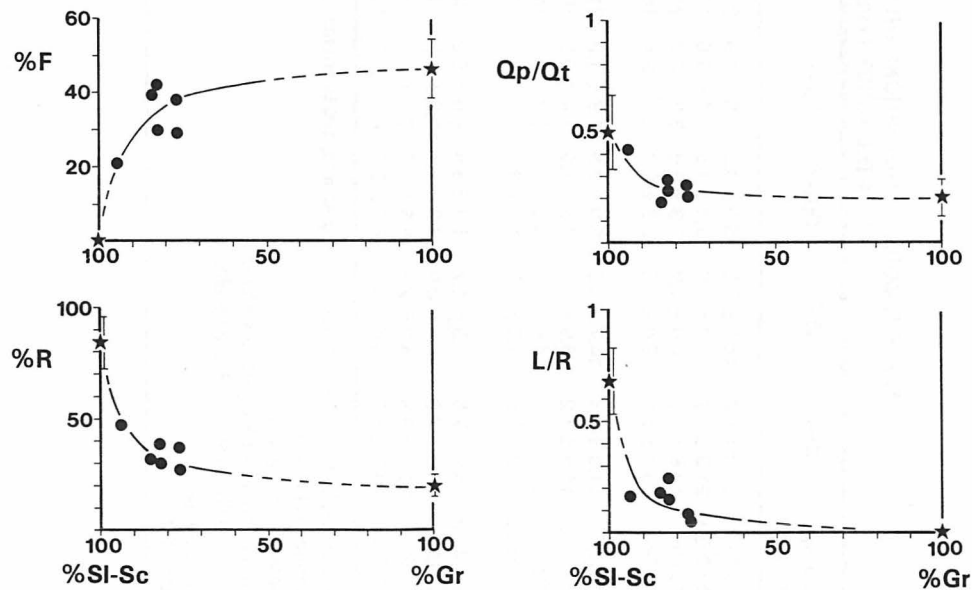


Figure 5. Compositional characteristics of mixed (granitoid + slate-schist) derived sands versus percentage outcrop area of granitoid bedrock in the source terrain. Stars represent the mean compositions (with standard deviations) of sands derived from a 100% granitoid (Gr) source terrain and from a 100% slate-schist (SI-Sc) source. R = total rock fragments; L = labile rock fragments. See Figure 4 for definition of other symbols.

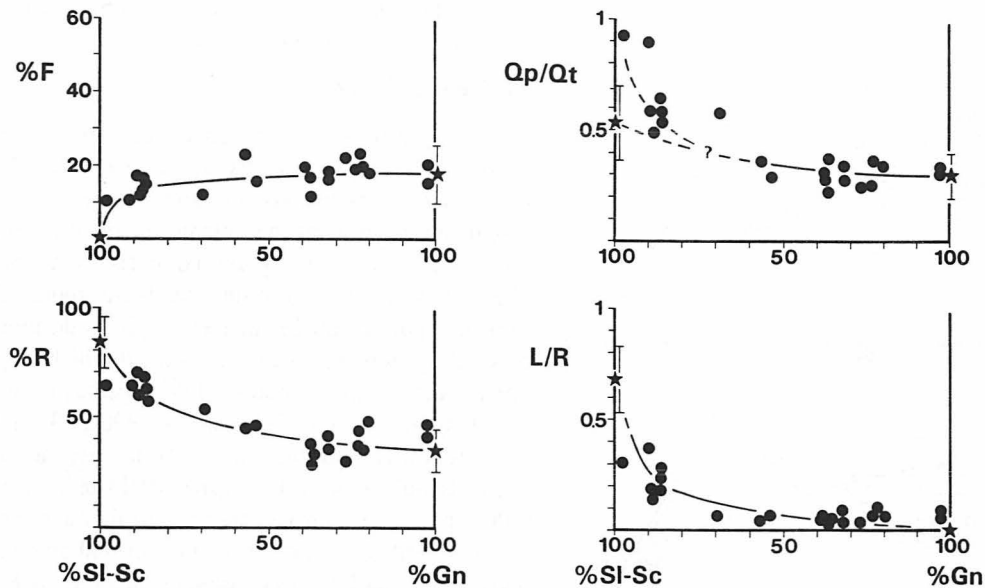


Figure 6. Compositional characteristics of mixed (gneiss + slate-schist) derived sands versus percentage outcrop area of gneiss bedrock in the source terrain. Stars represent the mean compositions (with standard deviations) of sands derived from a 100% gneiss (Gn) source terrain and from a 100% slate-schist (SI-Sc) source. Symbols as in Figures 4 and 5.

Among sands derived from the (Gr + Gn) source terrains, the percentage of rock fragments and polycrystalline quartz increases with increasing percentage of gneiss in the source area, whereas the feldspar content decreases (Fig. 4). However, the higher plagioclase content of granitoid with respect to gneissic rocks causes the K/P ratio (Dickinson, 1985) to rise with an increase of the proportion of gneissic bedrock at the source. In order to analyze modal composition of the sands in the QFR diagram, the samples have been grouped, according to the relative abundances of the bedrock types, in (Gr<sub>70-50</sub>)-derived and (Gr<sub><50</sub>)-derived sands (Fig. 7, above). Mean modal composition of these two groups are Q<sub>34</sub>F<sub>39</sub>R<sub>27</sub> and Q<sub>36</sub>F<sub>30</sub>R<sub>34</sub>, respectively. Compositions of sands derived from this type of compound source plot roughly on a straight line linking the compositions that characterize the pure (granitoid or gneiss) end member sands. Compositional trends in the diagrams in Figures 4 and 7 (above) are near-linear. Mean compositional values on the trend line in the QFR diagram are roughly proportional to the percentage of granitoid or gneiss in the source area. This is due to the similar composition and crystal size of the two parent rock types and points to their similar potential to generate sand.

#### Granitoid + slate-schist (Gr + SI-Sc)-derived sands

Sources characterized by an association of (Gr + SI-Sc) are rare in the Central System. Six samples derived from sources with a limited range in abundance in granitoid and slate-schist (Gr<sub>5</sub> + SI-Sc<sub>95</sub> to Gr<sub>30</sub> + SI-Sc<sub>70</sub>) have been analyzed. Nevertheless, the compositional data of these sands are particularly significant, when compared to those derived from simple (granitoid or slate-schist) sources (Fig. 5). In this case compositional trends strik-

ingly diverge from linearity. For instance, a small increase in the abundance of granitoid bedrock produces an important increase in feldspars (K-feldspar and plagioclase) and a disproportionate diminution of labile rock fragments, thus resulting a clear dominance of granitoid-derived grain types. The mean modal composition of sands derived from (Gr<sub>30-10</sub> + SI-Sc<sub>70-90</sub>) terrains is Q<sub>28</sub>F<sub>36</sub>R<sub>36</sub>. The modal composition of one sand sample derived from a (Gr<sub>5</sub> + SI-Sc<sub>95</sub>) source is Q<sub>28</sub>F<sub>22</sub>R<sub>50</sub>. Plotting these values and the means of the simple granitoid-derived and slate-schist-derived sands in the QFR diagram permits the development of the compositional trend (Fig. 7, center). It is evident from the diagram in Fig. 7 that no more than a 5% of granitoid in the source area is needed to produce sands with a modal composition near the midpoint of the trend line and that an important shift toward the mean composition of sands derived from pure granitoid terrains results when the granitoid proportion tends toward higher values.

#### Gneiss + slate-schist (Gn + SI-Sc)-derived sands

Variations in abundance of the different grain types in (Gn + SI-Sc)-derived sands show trends similar to those found in sands derived from (Gr + SI-Sc) sources (Fig. 6, Table 2). Feldspar content markedly rises (from negligible to more than 10%) when gneiss appears as bedrock in the source area. Beyond a value of about 15% of gneissic bedrock, the feldspar content remains relatively stable. A similar, but inverted, trend is observed in the case of polycrystalline quartz grains and rock fragments. Moreover, when gneiss exceeds 20% of the source area the content of labile rock fragments in the sands becomes insignificant. On the other hand, the Q<sub>p</sub>/Q<sub>t</sub> ratio characterizing pure slate-schist derived

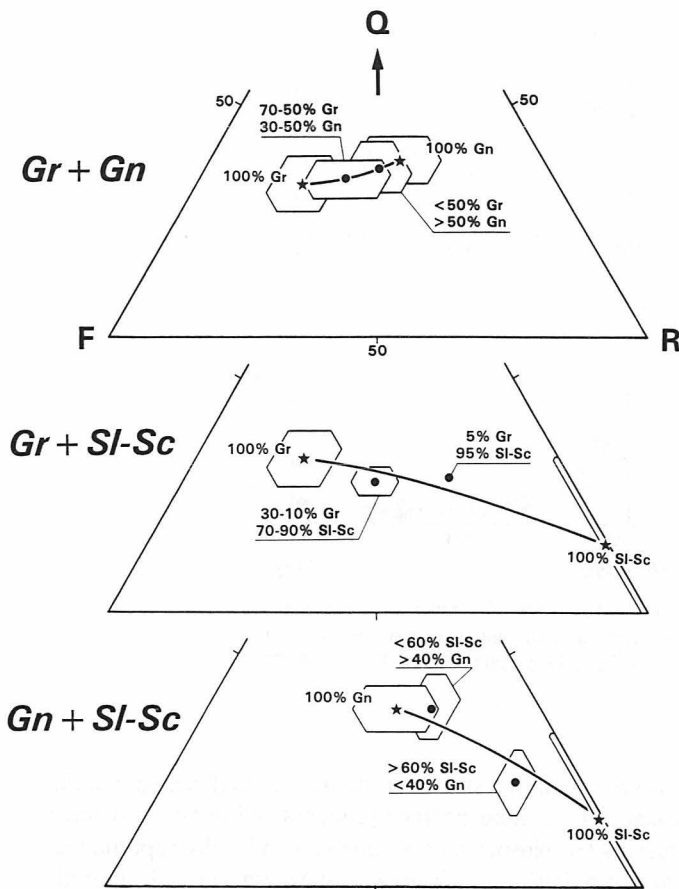


Figure 7. QFR compositions (mean and standard deviation) of sands derived from the three different source rock associations considered. Above, granitoid + gneiss (Gr + Gn); center, granitoid + slate-schist (Gr + Sl-Sc); below, gneiss + slate-schist (Gn + Sl-Sc). For clarity, compositional data concerning individual sand samples have been grouped into classes according to the relative abundance of the two bedrock types at the sources. Stars represent end member compositions of sands derived from simple (single lithology) sources (from Fig. 3).

sands is lower than expected, if compared with  $Q_p/Q_t$  values of sands from terrains with gneiss  $<20\%$ . However, the mean composition for slate-schist-derived sand has been obtained from data relative to 13 sands derived from slates and schists with different percentages of interbedded quartzitic rocks. This probably explains the low  $Q_p/Q_t$  index observed. Mean compositions of  $(Gn_{>40} + Sl-Sc_{<60})$ - and  $(Gn_{<40} + Sl-Sc_{>60})$ -derived sands are  $Q_{38}F_{20}R_{42}$  and  $Q_{27}F_{10}R_{63}$ , respectively. The trend line that links the means of exclusively gneiss derived and slate-schist derived sands in the QFR diagram (Fig. 7, below) is similar in shape but shorter than that established for sands generated from (Gr + Sl-Sc) sources. This reflects the greater potential of gneiss to yield rock fragments compared to granitoid lithologies. As in (Gr + Sl-Sc)-derived sands, modal compositions are not directly proportional to the relative percentages of gneiss and slate-schist in the source area. Sands derived from terrains with no more than a

40% of gneiss have a composition similar to that of sands generated from simple gneissic sources.

## INTERPRETATION

The compositional characteristics of first-cycle sands derived from the three types of dual sources considered show that no simple relation exists between sand composition and the percentage of surface area of the different bedrock types at the source. Each bedrock type (i.e., granitoid, gneiss, and slate-schist) has a different potential to produce sand-size grains. Sands derived from compound sources therefore will be dominated by grains proceeding from the rock type with the highest potential. This potential is mainly a function of the specific properties of a given rock type (Cooke and Doornkamp, 1990, p. 325). Crystal size in the parent rock controls the size of the mechanically weathered products and rocks with a mean crystal size in the range of 2.0 to 0.062 mm have a greater capacity to produce sand than others characterized by a smaller average crystal size (e.g., granitoids versus slates and schists). Another factor is rock isotropy. The virtual isotropy of plutonic rocks causes them to disintegrate preferentially along crystal boundaries, thus providing a great amount of sand-size monomineralic grains. In contrast, fabric heterogeneities (such as foliation and oriented microfibrils) typical of metamorphic rocks produce additional unstable surfaces. In fact, slates, schists, and gneisses tend to break preferentially along such surfaces, providing either coarse-clastic debris or products smaller than sand-size, with a consequent impoverishment of the sand fraction (e.g. Palomares, 1988; Palomares et al., 1990). Chemical stability and hardness of rock-forming minerals constitute a third important factor that affects the volume of sand generated. Low-stability minerals release high quantities of silt- and clay-size clasts, apart from soluble products, thus decreasing the sand generation potential of the parent rock.

In order to make allowance for the contribution of a particular bedrock constituent of a compound source area to the derivative sand, we propose the concept of sand generation index (SGI). It is convenient to express the SGI of a given bedrock type A of a dual source A + B in terms of the outcrop area of A required to produce a sand whose modal composition represents the average between the modes of the sands derived from simple A and B sources. Average modal compositions can be read from the QFR diagram (Fig. 3), and corresponding area percentages subsequently assessed from binary diagrams, such as shown in figures 4, 5, and 6. Thus,

$$SGI_{A(A+B)} = \frac{(S_A + S_B)}{S_A}$$

where  $SGI_{A(A+B)}$  denotes the SGI of A referred to a dual source constituted by the association A + B;  $(S_A + S_B)$ , the total surface area of the source terrain and  $S_A$ , the surface area occupied by A.

For example, in a source area constituted by (Gr + Sl-Sc), only about 5% outcrop area of granitoid bedrock is needed to obtain a sand with a modal composition of  $Q_{28}F_{22}R_{50}$  (the average between that of an exclusively granitoid-derived and that of a pure slate-schist-derived sand). Consequently  $SGI_{Gr(Gr +$

**TABLE 3. SAND GENERATION INDEX (SGI) AND RELATED PARAMETERS FOR GRANITOID, GNEISSES, AND SLATE-SCHISTS IN THE THREE BEDROCK ASSOCIATIONS CONSIDERED**

Associated Rock Types in the Source Area	Average Modal Compositions of Sands Derived from Simple Sources*	Surface Area Corresponding to Average Composition† (%)	SGI
Granitoid + gneiss	Q <sub>35.5</sub> F <sub>37</sub> R <sub>27.5</sub>	Gr 40–50	2.0–2.5
		Gn 50–60	1.66–2.0
Granitoid + slate-schist	Q <sub>23.5</sub> F <sub>24</sub> R <sub>52.5</sub>	Gr 5–7	14.28–20.0
		Sl-Sc 93–95	1.04–1.07
Gneiss + slate-schist	Q <sub>24</sub> F <sub>14</sub> R <sub>60</sub>	Gn 15–20	5.0–6.66
		Sl-Sc 80–85	1.25–1.77

\*From Figure 3.  
†From Figures 4, 5, and 6.

Sl-Sc) is between 14 and 20 ( $S_{Gr} + S_{Sl-Sc}/S_{Gr}$ ), whereas  $SGI_{Sl-Sc}(Gr + Sl-Sc)$  is about 1 ( $S_{Gr} + S_{Sl-Sc}/S_{Sl-Sc}$ ). In other words, granitoid rocks are 14 to 20 times more efficient in producing sand than are slates and schists. Table 3 shows the SGI values of the three bedrock types in the three associations considered in this study. It is obvious from the above definition that relative values result, rather than absolute (rock-specific) values. Granitoid has the highest SGI when associated with slate-schist. Gneiss generates four times less sand than granitoids do when associated with slate-schist. As expected, in both cases slate-schist bedrocks turn out to be a minor sand source when compared with granitoid and gneissic bedrocks. SGI values of granitoid and gneiss are similar when these two lithologies are present in the source area.

It is essential to remember that our analytical data refer to the medium-sand fraction. The SGI values listed in Table 3, therefore, only reflect the potential of a rock to generate grains in that size range. Complementary studies concerning the coarse- and fine-sand fractions will be attempted in the future. Furthermore, our results are based on sands from first- to sixth-order streams between <1 and 15 km in length, and thus the effects of transport on sand composition are negligible. Longer transport distances evidently cause the content of rock fragments and feldspar to decrease (Cameron and Blatt, 1971; Breyer and Bart, 1978; Mack, 1978), with an attendant increase in quartz grains. Accordingly, with increasing transport distances, one has to expect a progressive shift toward the Q apex of the compositional fields and trend lines illustrated in Figure 7. Humid climatic conditions are likely to produce a parallel shift (Suttner et al., 1981; Basu, 1985; Grantham and Velbel, 1988).

In spite of the above arguments, our data suggest that the model composition of sands and sandstones (in particular arkoses) may be determined by a rock type that represents only a subordinate portion of the source area and, thus, attempts to estimate sourceland composition directly from QFR plots are hazardous. Our results call for a critical revision of conventional paleogeographical and paleogeological interpretations based on detrital modes. A case in point is the lower Triassic Buntsandstein

in the Iberian Range, a formation including arkoses, subarkoses, and quartzarenites, generally with less than 12% of unstable low-rank metamorphic rock fragments (slate and micaceous schists) (Arribas et al., 1985). Traditionally, provenance of these deposits has been interpreted in terms of a "principally" granitic-gneissic source, with "minor" contributions of low-rank metamorphic rocks. In view of the results of this study, such straightforward assertions are no longer warranted and, unless carefully documented, caution is recommended when using semiquantitative terms (such as dominant, principal, minor) in provenance interpretations.

## CONCLUSIONS

1. The comparison of modal compositions of first-cycle sands derived from source areas consisting of one and two lithologies (simple and dual crystalline sources, respectively) provide information concerning the relative capacity of different bedrock types (granitoid, gneiss, and slate-schist) in generating medium sand-size grains.

2. The concept of sand generation index (SGI) is introduced. SGI permits specification of the capacity of a given bedrock type to produce sand with respect to others in a compound source area.

3. SGI of a specific bedrock type, such as defined here, varies with respect to the source rock association. Thus, in case of a granitoid + slate-schist source SGI of granitoid is 14 to 20, whereas the SGI of slate-schist is about 1. By contrast, the SGI of granitoid is 2.0 to 2.5 when this rock type occurs in association with gneiss in the source area. In this case the SGI of gneiss is in the range of 1.66 to 2.00. Finally, in a gneiss + slate-schist association, the SGI of gneiss is 5.0 to 6.66, and the SGI of slate-schist is 1.25 to 1.77.

4. It is shown that the overall composition of a sand or sandstone in cases can be critically influenced by a bedrock type that constitutes only a minor portion of the source area. Quantitative estimates concerning the sourceland geology that are based exclusively on QFR plots may therefore be incorrect.

## ACKNOWLEDGMENTS

We are grateful to Glen Hieshima, who kindly reported on our ideas at the 1991 annual meeting of the Geological Society of America. Abhijit Basu and Amparo Tortosa helped and encouraged us during research and in the preparation of the manuscript. The manuscript was read critically by O. Kálin and reviewed by W. C. James and S. W. Young; we greatly appreciate the helpful comments, corrections, and criticisms.

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