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Sands in the Alboran Sea: A Model of Input in a Deep Marine Basin

Daniel Jean Stanley, Gilbert Kelling, Juan-Antonio Vera, and Harrison Sheng

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ABSTRACT

Stanley, Daniel Jean, Gilbert Kelling, Juan-Antonio Vera, and Harrison Sheng. Sands in the Alboran Sea: A Model of Input in a Deep Marine Basin. *Smithsonian Contributions to the Earth Sciences,* number 15, 51 pages, 23 figures, 8 tables, 1975.—The Alboran Sea, an almost totally land-enclosed, mountain-bounded (Rif, Betic ranges) basin, lies east of Gilbraltar in the westernmost Mediterranean. A petrologic study of the sand fraction in river, river mouth, and beach samples collected on the coast of the Alboran Sea defines the composition and distribution of the principal light and heavy mineral groups along its margins. The investigation details 20 mineralogical provinces on the southern Iberian and northern Moroccan margins and the Strait of Gibraltar sector and identifies the major source terrains and fluvial and marine point sources of terrigenous sediment entering the basin.

Significant sample-to-sample changes in the proportion of mineralogical components are attributed to marine processes, particularly nearshore currents, which move sands laterally along the coast and, while so doing, modify the proportions of light and heavy mineral components. Lateral trends observed within Moroccan and Spanish mineralogical provinces provide evidence on the actual sense of nearshore sediment dispersal. Marine transport agents have a more pronounced effect on the light mineral fraction, while even unstable heavy mineral species appear to suffer less modification as a result of the transport in the marine environment. The paths followed by the sands between source terrain and final depositional site in deepwater environments are complex ones. A comparison of mineral assemblages in coastal sands and in sands in deep-sea cores shows a provenance from the Serranía de Ronda complex in the Betic range west of Málaga. After initial deposition on the coast, these river-borne sediments are transported in a southwestward direction toward Gibraltar and then eventually are funneled downslope in a southeastward direction toward the Western Alboran Basin through the Gibraltar Canyon and submarine valley.

In geological terms, the Alboran Sea study can serve as a model for sedimentation in one type of elongate enclosed basin bounded by regions of high relief. Although the geographic and geologic configuration of the Alboran Sea and contiguous land conforms to a multisource basin model, the transport paths of sediment since the late Quaternary have been essentially longitudinal. This longitudinal input, with filling as a result of currents primarily from the Strait of Gibraltar sector, is independent of a major delta source and is thus unlike many elongate, deep-sea basins examined in present oceans and troughs (including flysch) mapped in the ancient rock record.

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Contents

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Introduction

This investigation, an outgrowth of sedimentological and oceanographic surveys of the Alboran Sea between Morocco and Spain, summarizes the results of a mineralogic analysis of coastal samples collected along the southern Spanish margin and the northern coast of Morocco in the westernmost Mediterranean Sea. The primary purpose of the study was to identify the principal source terrains of the sediments derived from the adjacent mountainous sectors into this almost totally enclosed sea (Figure 1). To date, little is known concerning the mineralogy and distribution of sediments along the margins of the Alboran Sea. This study is intended to define the major point sources of terrigenous sands entering the Western Alboran Sea from the Strait of Gibraltar and the Moroccan and Spanish sectors. In turn, this involves both determination of the predominant direction of sediment movement along the coast and the identification of the major transport paths from the coast seaward into the deeper regions of the Western Alboran Sea. The relative efficacy of heavy and light minerals in the context of provenance and dispersal is also investigated.

Another purpose of this study was to better evaluate the factors influencing provenance and dispersal in analogous ancient marine basins whose sediments are preserved in the fossil record. The similarity between the sediments in the Western Alboran Basin plain, a flat, deep (just over 1500 m) oval (24 by 37 km) basin, and some ancient flysch deposits has been noted elsewhere (Stanley et al., 1970; Stanley and Unrug, 1972). The mineralogical study in the Alboran Sea is of potential value geologically because it enables the sand-sized sediments, materials initially transported by rivers to the coast and subsequently modified by marine coastal agents, to be traced downslope to deeper environments in an almost completely enclosed system. Thus, the Alboran case can serve as a model for a type of multisource dispersal system possibly applicable to some ancient basins, including flysch troughs (Stanley and Unrug, 1972, figs. 37–40).

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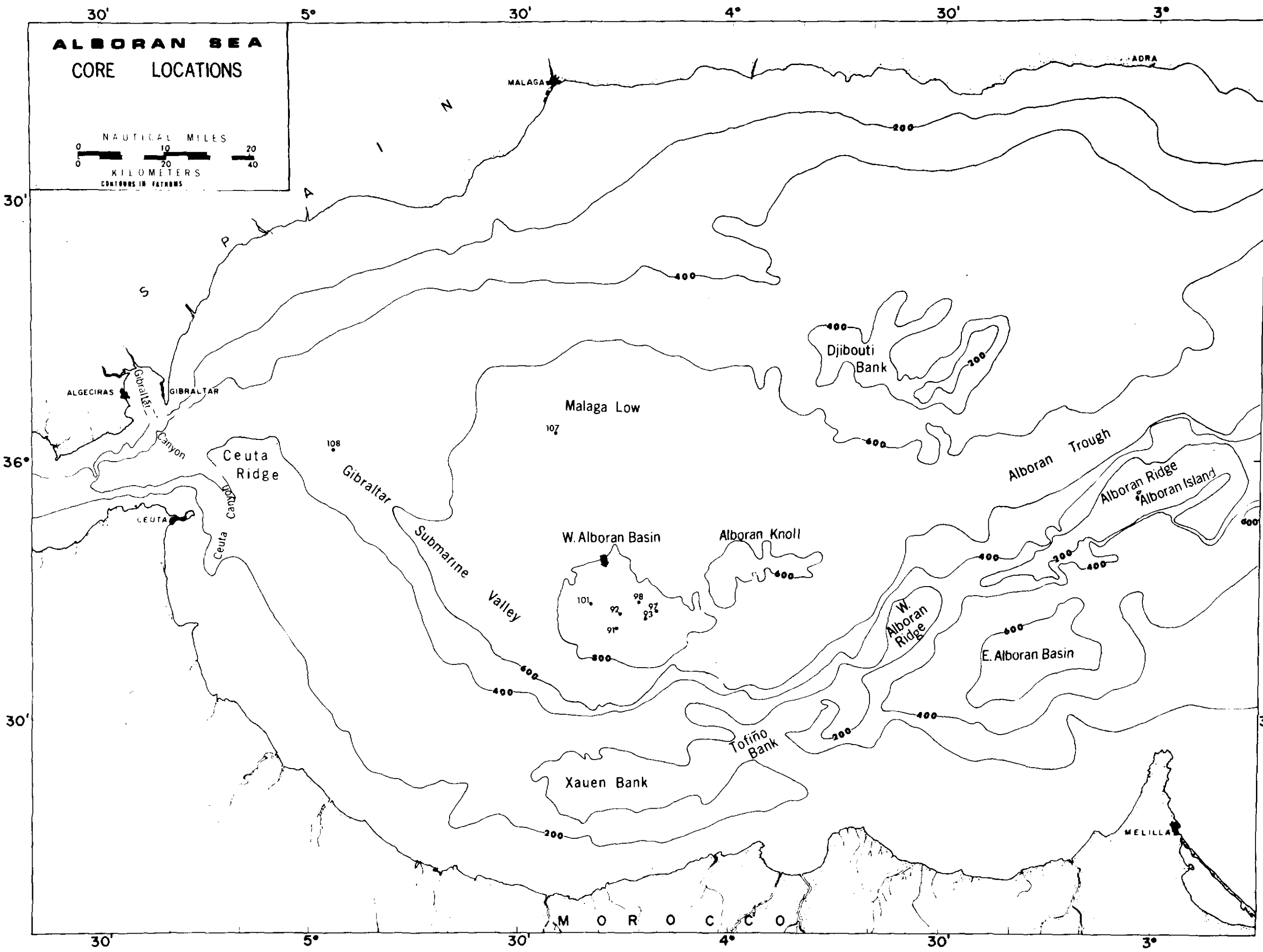


FIGURE 1.—Chart showing core localities and major geographic features in the Alboran Sea and Strait of Gibraltar region. Details on cores available in Huang and Stanley (1972). (Geographic names cited in the text are shown here and on Figures 2 and 3.)

sis, and to Professor J. F. Fontboté, University of Granada, for providing us with valuable regional data, maps, and references, and for his review of the text. The 3.5 kHz subbottom records were collected on 1972 cruises of the USNS *Lynch,* and aerial photographs were supplied by the Defense Intelligence Agency, Washington, D. C. Dr. A. Maldonado, University of Barcelona, also reviewed the manuscript.

Funds for this study, part of the Mediterranean Basin Project, including travel to Spain and Morocco and the collecting and processing of samples, were provided to one of us (D. J. S.) by Smithsonian Research Foundation grants (FY 1971) 472350 and (FY 1972) 430035. Support was also provided (G. K.) by the United Kingdom Natural Evironment Research Council and the Royal Society of London.

General Considerations

The southern flank of the Betic Cordillera bordering the southern Spanish margin (elevations to over 3000 m) and the northern flank of the Rif (maximum elevations in excess of 2000 m) are cut by numerous seasonally active rivers (or oueds) and torrents capable of carrying material of mud to boulder size directly to the coast. The study was planned so that sand-size material collected in these rivers and along the coast of both margins eventually could be compared to sand collected offshore in cores from the deeper Alboran Sea.

A review of the major geologic units that provide sedimentary material is necessary to properly interpret the provenance of coastal samples. The major stratigraphic-structural units mapped in the Betic Cordillera and the Rif chains are depicted in Figures 2 and 3. Each of these units can be distinguished on the basis of gross lithology and mineralogy, which permits the composition of river mouth and coastal sands to be identified with outcrops of specific units.

The major stratotectonic units comprising the Betic Cordillera source terrains (Figure 2) are defined on the basis of investigations of many workers. Among the more recently published regional studies pertinent to the Iberian margin, we can cite the following: Kockel (1963), Mollat (1965), Dürr (1967), Hernández-Pacheco (1967), Boulin (1968), Durand-Delga (1968), Hoppe (1968), Aldaya (1969), Egeler and Simon (1969), Jacquin (1970), Aldaya and Vera (1971), Fontboté (1971), González-Donoso et al. (1971), Orozco (1971), Puga (1971), and Loomis (1972). A summary of the major units providing sediments to the Spanish coast is presented in the Appendix.

The general geology of the Moroccan margin illustrated in Figure 3 is based on the published maps of the Service Géologique du Maroc, together with more detailed discussions by Fallot (1937), Fallot and Marín (1952), Milliard (1959), and Durand-Delga and Kornprobst (1963).

Sampling and Methodology

Samples on the Iberian margin were collected at the mouths of major rivers and on beaches between the Strait of Gibraltar and Adra (i.e., from 3° to 5°37′W longitude) in the region popularly called the Costa del Sol. Sampling here is facilitated by the presence of a major coastal road (Spanish highway no. 340) that follows the shoreline along much of this area. The spacing between Spanish coastal samples ranges from 2 to 6 km; the average distance between stations is 3 to 4 km (position given in Table 1; see also Figure 2). The major rivers, principal fluvial drainage basins, and sample localities are shown in Figures 2 and 4. The name of each drainage basin is derived from the principal river. Several of the smaller morphological basins without major rivers bear no name.

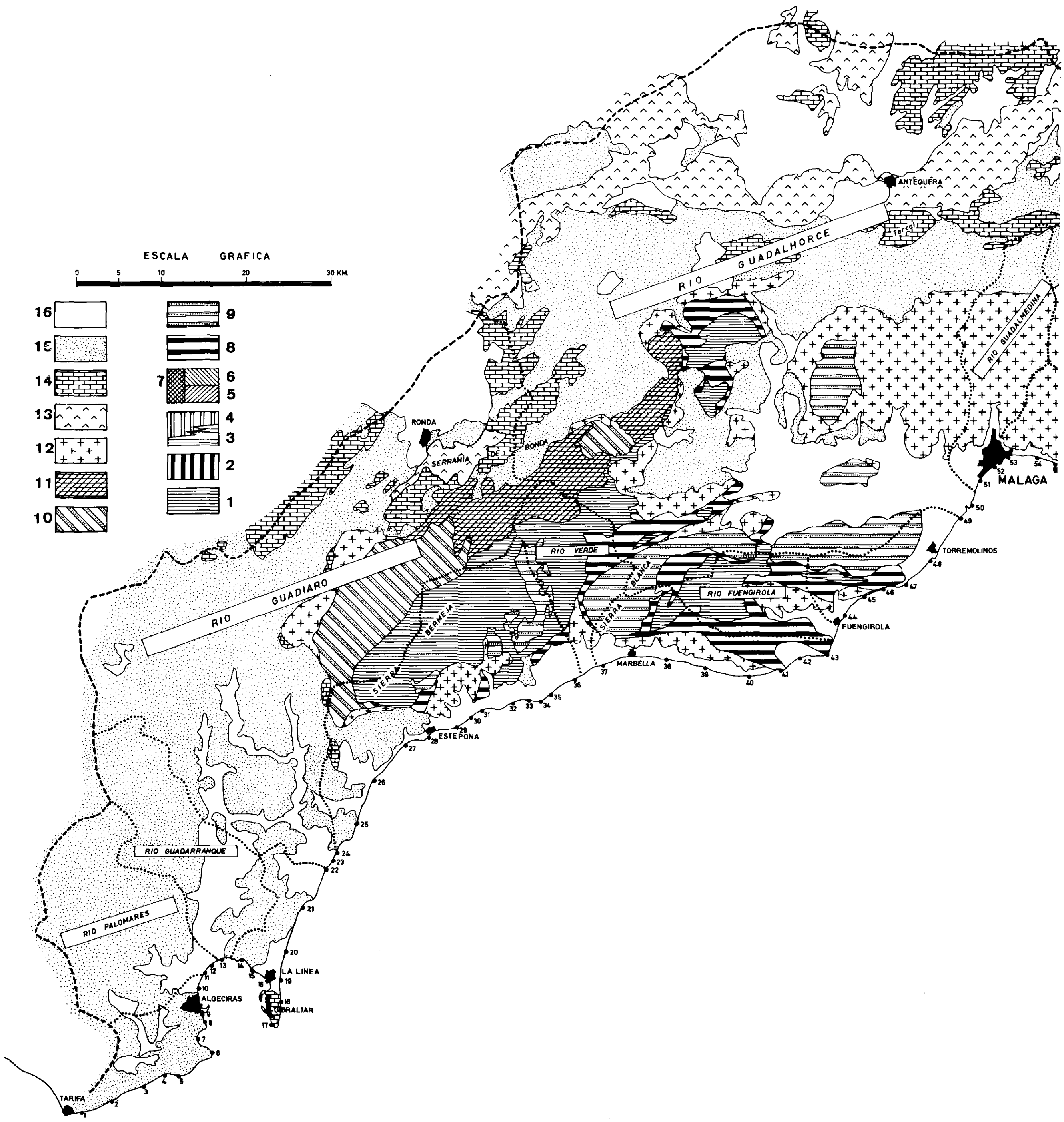
It is useful to compare the mineralogy of riverborne material and that of sediment at the same river mouths along the coast. In this respect, six sample stations were occupied between the Calena (near Marbella) and the Genal-Guadiaro rivers west of Marbella. The rivers sampled include, from east to west, the Calena, Guadaiza, Guadalmansa, Padrón, Enmedia, and Genal-Guadiaro (rivers between 7 and 4 on Figure 4); sampling stations were made close to where Highway 340 crosses the rivers. Two samples were collected about 100 m apart at each of the six stations. The results are listed in Tables 4 and 5 and illustrated in Figures 5 and 6.

In similar fashion, samples were collected in the major rivers and river mouths and along the coast on the Moroccan margin between Cap Spartel and Al Hoceima (also known as Al Hucemas) from 4°10′ to 5°50′W longitude (Figure 3, Table 2). However, the coastal area of northern Morocco remains considerably less accessible than that of Spain, and as a consequence the sampling is neither as regular or as complete, although we believe that it provides representative data.

The grain size of the 113 Spanish and 38 Moroccan river and littoral samples examined varies from muddy sand to granule grade. Consequently, only the 0.062 to 0.25 mm fraction (very fine to fine sand) was selected for petrologic study in order to minimize size-sorting problems and thus to provide a better evaluation of regional changes in mineralogy.

It is in this fraction that the heavy minerals, sensitive indicators of provenance, are generally concentrated. The granules and pebbles, common in most of the samples, include a wide variety of metamorphic as well as carbonate rock types; the petrology of these coarse fractions is not examined in the present study.

Heavy minerals were separated by the standard heavy liquid method and their percent (by weight) calculated. Light minerals were mounted on glass slides, ground and stained according to the method of Hayes and Klugman (1959), in order to identify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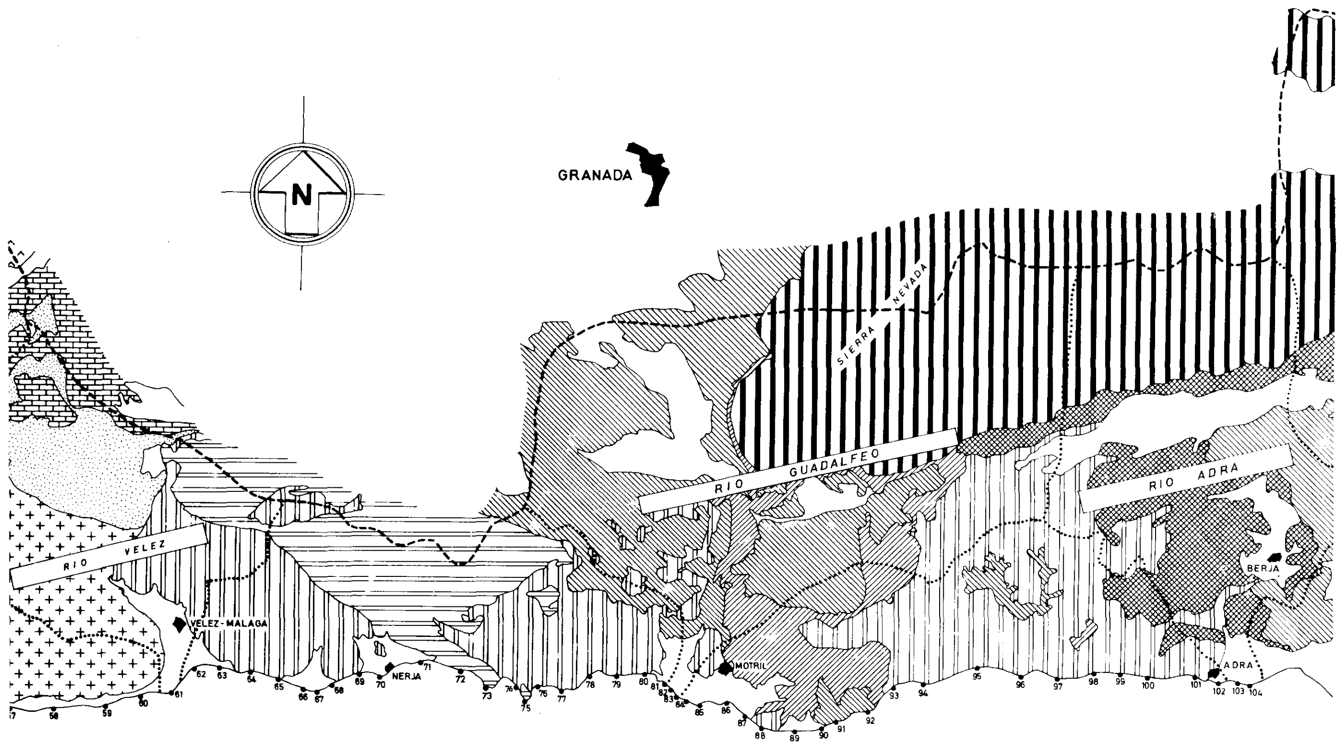


FIGURE 2.—Geological map of the southern coast of Spain between Adra and the Strait of Gibraltar showing the major tectonic-stratigraphic (including lithologic) units in the Betic Cordillera. The map is based on geologic maps published by the Instituto Geológico y Minero de España at a scale of 1:200,000 and modified by J. M. Fontboté and J.-A. Vera. Lithology of the different units are described in the Appendix. Coastal and river sample localities are also shown (see Table 1). [Broken line = Boundary between the major Atlantic and Mediterranean drainage systems. Dotted line = Boundary delineating the principal Mediterranean fluvial basins in the study area; the basins are named after the major rivers flowing southward toward the Mediterranean Sea; those basins with rivers and torrents of only minor importance remain unnamed. *Internal Zones:* 1, Peridotite (ultrabasic) Complex; 2, Nevado-Filábride Complex, metamorphic rocks; (3–7, Alpujárride Complex, eastern sector); 3, Paleozoic, with prevailing dolomite and marble; 4, Paleozoic, with prevailing micaschist and quartzite; 5, Permian-Werfenian, phyllite and quartzite; 6, Middle and Upper Triassic, limestone and/or dolomite; 7, Permo-Trias, undifferentiated (5) and (6); 8, Maláguide Complex, Pre-Cambrian (?), miscaschist and gneiss; 9, Sierra Blanca Unit; 10, Casares Unit (Alpujárride Complex, western sector); 11, Las Nieves Unit; 12, Maláguide Complex, Paleozoic (also includes, locally, a thin Mesozoic-Tertiary cover). *External Zones:* 13, Triassic ("Germanic facies"); 14, Jurassic, limestone and marly limestone; 15, Cretaceous-Paleogene-lower Miocene, mainly marl and marly limestone; also sandstone and limestone. *Post-Orogenic Sequences:* 16, Neogene-Quaternary, mainly detrital sedimentary rocks and sediments.]

TABLE 1.—*Sediment sample localities on the southern Mediterranean coast of Spain and vicinity of the Strait of Gibraltar, from west to east* (see Figure 2)

Sample Number (On Fig. 2)	General Description of Sample Locality on Southern Spanish Coast and Gibraltar	Wave Direction (October 1970)	Dominant Beach Lithology
S 1	Rocky beach east of Tarifa along rugged coastline; rocky offshore	130°	Pebbles and larger
S 2	Beach at base of mountainous coast near Arroyo Viñas about 4 km east of Tarifa; rocky offshore	105°	Sandy pebbly
S 6	Coast near Punta del Carnero (a mountainous cape), near old destroyed jetty	70°	Pebbly
S 7	Ensenada de Getares, near mouth of Arroyo del Lobo, small delta	95°	Sand
S 8	Just north of Punta de San Garcia, Algeciras Bay, same latitude as Europa Point	15°	Pebbles and larger
S 9	Algeciras, south of jettys	125°	Pebbly sand
S10	Beach at base of hill, just north of Algeciras	95°	Sand
S11	Mouth of Palmones River, Algeciras Bay	115°	Sand
S12	Beach between Palmones and Guadarranque rivers, Algeciras Bay	130°	Sand
S13	Mouth of Guadarranque River, Algeciras Bay	160°	Sand
S14	Northern Algeciras Bay, near large petroleum refinery; near Arroyo de los Lecheros	150°	Sand
S15	Northern Algeciras Bay near El Campamento; low coastal plain	190°	Sand
S16	Northeast Algeciras Bay near La Línea; low coastal plain	–	Sand
G 4	Camp Bay, southwest side of Gibraltar, northwest of Europa Point	–	Sand
G 1	Beach from Sandy Bay, east side of Gibraltar	–	Sand
G 3	Dune sand (Pleistocene?), just south of Catalan Bay, east side of Gibraltar	–	Sand
G 2	Beach at southern end of Catalan Village Bay, east side of Gibraltar	–	Sand
G 5	Eastern Beach, east side of Gibraltar, south of La Línea	–	Sand
S19	Near La Línea, near the Frontier, northeast of Gibraltar	90°	Sand
S20	North of La Línea, near Torre de Senales; dunes along coast	85°	Sand
S21	Beach at base of hills, Punta Carbonera	110°	Sand
S22	Dunes along coast just south, Guadiaro River	180°	Pebbly sand
S23	Mouth of Guadiaro River	180°	Pebbly sand
S24	Beach north of Guadiaro River; low deltaic coastal plain	180°	Pebbly sand
S25	Playa del Negro, north of Punta Chullera	170°	Pebbly sand
S26	Beach near mouth of Rio de Manilva; coastal plain below hills	170°	Pebbly sand
S27	West of Estepona, near Arroyo de Guadalobón	175°	Pebbly sand
S28	Estepona, near port	175°	Pebbly sand
S29	Narrow rocky beach west of Río del Padrón	130°	Sandy cobble (>10 cm)
S30	Mouth of Río del Padrón; small water bodies present	130°	Pebbly sand
S31	Near Río del Castor; semi-desert physiography	130°	Pebbly sand
S32	San Pedro de Alcántara, east of Rio Guadalmansa	130°	Pebbly sand
S33	Arroyo de Dos Hermanas, west of Rio Guadalmina	160°	Pebbly sand
S34	Mouth of Río Guadalmina; river sediments form delta	140°	Pebbly sand
S35	Beach near Arroyo del Chopo	130°	Pebbly sand
S36	Beach near mouth of Río Verde, west of Marbella	120°	Pebbly sand
S37	On Ensenada de Marbella, west of Marbella; near Arroyo de Nagueles	140°	Pebbly sand
S38	Beach east of Marbella, near Río Real	140°	Sand
S39	Beach near Chalets Costa Bella	150°	Sand
S40	Beach near Punta Ladrones	150°	Sand
S41	Beach near Torre de Calahonda	125°	Shelly pebbly sand
S42	Beach at Ensenada de Cala del Moral	180°	Shelly pebbly sand
S43	Cabo de Calaburra, west of Río de Fuengirola	190°	Shelly sand
S44	Beach at Fuengirola, west of Arroyo Real	160°	Sand
S45	Beach near Arroyo de Presas, Torre Blanca del Sol	175°	Pebbly sand
S46	Beach near Torre Benalmadena	170°	Shelly pebbly sand
S47	Arroyo de la Miel, west of Torremolinos	170°	Sand
S48	Beach at Torremolinos, Playa de la Carihuela	175°	Sand
S49	Beach west of Guadalhorce River, on delta	120°	Pebbly sand
S50	Beach east of Guadalhorce River, on delta; west of Málaga (industrial zone)	120°	Pebbly sand
S51	Beach west of Málaga, west of Guadalmedina River	110°	Pebbly sand
S52	Mouth of Guadalmedina River, Málaga	115°	Pebbly sand
S53	East of Malaga, Málaga Bay	150°	Sandy pebbly
S54	Near El Palo, Málaga Bay, at mouth of dry torrent	210°	Pebbly sand
S55	Beach west of La Victoria, Málaga Bay	190°	Pebbly sand
S56	Beach near Cala del Moral, Málaga Bay	180°	Pebbly sand
S57	Beach at La Victoria, Málaga Bay	170°	Pebbly sand
S58	Beach near Estación Benagalbón	165°	Pebbly sand
S59	Beach off plain, east of Torre Moya	190°	Sandy pebbly
S60	Beach, west of Río Vélez	190°	Sand
S61	Mouth of Río Vélez, on small delta west of Torre del Mar	200°	Sandy pebbly
S62	Torre del Mar, east of Río Vélez	190°	Pebbles and larger
S63	Beach east of Torre del Mar and west of La Caleta	190°	Pebbly
S64	Narrow beach east of Río de Algarrobo	200°	Pebbly
S65	Beach west of Morche	220°	Pebbly and coarser
S66	Beach on delta, west of Río de Torrox	250°	Pebbly sand
S67	Mouth of Río de Torrox, on small delta	230°	Pebbly and coarser
S68	Beach east of Río de Torrox	220°	Pebbly and coarser
S69	Beach east of Punta de Torrox	220°	Sandy pebbly
S70	Mouth of Río Higuerón, on small delta	200°	Pebbly
S71	Beach east of Nerja, south of Maro	210°	Pebbly and coarser
S72	Beach off rocky high terrain, east of Maro	220°	Pebbly and coarser
S73	Beach on rocky point west of La Herradura	240°	Pebbly and coarser
S74	Beach at La Herradura	250°	Pebbly and coarser
S76	Beach east of Punta de la Mona and west of Río Verde	150°	Pebbly and coarser
S78	Beach east of Río Verde and Almuñecar	140°	Pebbly
S79	Small river south of Taramay	140°	Pebbly and coarser
S80	Beach west of Salobreña and La Caleta	160°	Sandy pebbly
S81	Beach on delta of Río Guadalfeo, south of Salobreña	155°	Sandy pebbly
S82	Beach at mouth of Río Guadalfeo	170°	Sandy pebbly
S83	Beach at mouth of Río Guadalfeo, on delta	165°	Pebbly sand
S84	Beach on eastern part of Río Guadalfeo delta	170°	Pebbly sand

TABLE 1.—(Continued)

Sample Number (On Fig. 2)	General Description of Sample Locality on Southern Spanish Coast and Gibraltar	Wave Direction (October 1970)	Dominant Beach Lithology
S 85	Beach at Glorieta, east of Río Guadalfeo delta	145°	Sandy pebbly
S 86	Coast at the Port of Motríl	155°	Sand
S 87	Beach at Torrenueva, southeast of Motríl	160°	Sandy pebbly
S 88	Beach on Cabo Sacratif, near light house	180°	Pebbly sand
S 89	Beach on Cabo Sacratif, off flat plain	140°	Sandy pebbly
S 90	Beach at Calahonda, at mouth of small river	125°	Pebbly and coarser
S 91	Beach east of Calahonda along rough coastline	170°	Pebbly and coarser
S 93	Beach at Castéll de Ferro, near Rambla Gualchos	120°	Pebbly and coarser
S 94	Beach east of Castéll de Ferro, along rough coast	150°	Sandy pebbly
S 95	Narrow beach east of La Mamola	120°	Pebbly sand
S 96	Beach at Punta Negra, near rocky coast	115°	Pebbly and coarser
S 97	Beach at La Rabita, at mouth of small river	150°	Pebbly sand
S 98	Narrow beach east of El Pozuelo	140°	Pebbly sand
S 99	Beach west of La Alcazaba	130°	Pebbly sand
S100	Beach at Cainos Bajos	135°	Sandy pebbly
S101	Beach west of Adra, near small port	160°	Pebbly and coarser
S102	Beach east of Adra	145°	Pebbly sand
S103	Beach on delta, west of Río Chico (R. Adra)	140°	Pebbly sand
S104	Near mouth of Río Chico (R. Adra), on delta	130°	Sandy pebbly

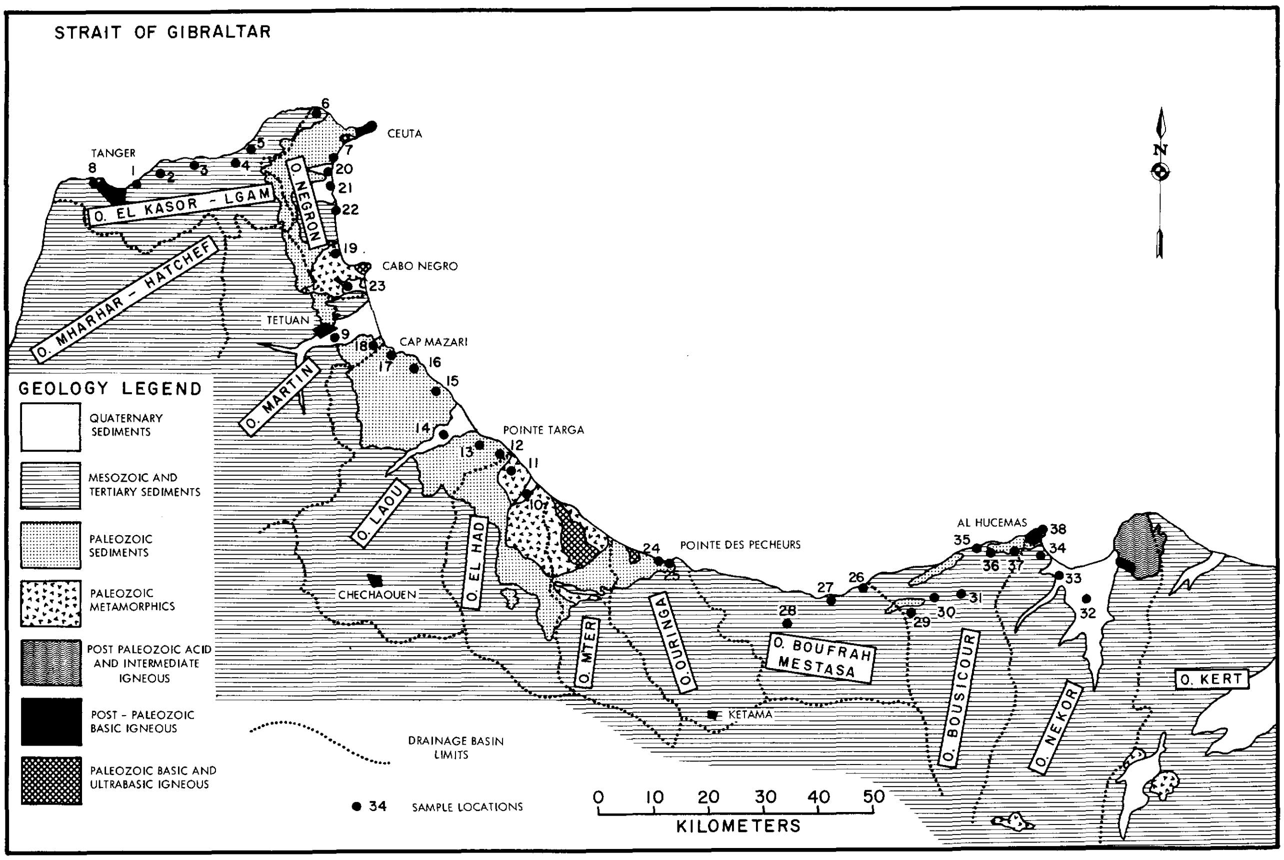


FIGURE 3.—Geological map of the northern margin of Morocco showing major stratigraphic sequences (based on maps by Fallot, 1937; Fallot and Marín, 1952; and others). Coastal and river sample localities also shown (see Table 2). Note that for clarity, the submarine outcrops of basic/ultrabasic rocks around Cabo Negro deduced by Milliard (1959) and others are also shown as occupying the peninsula.

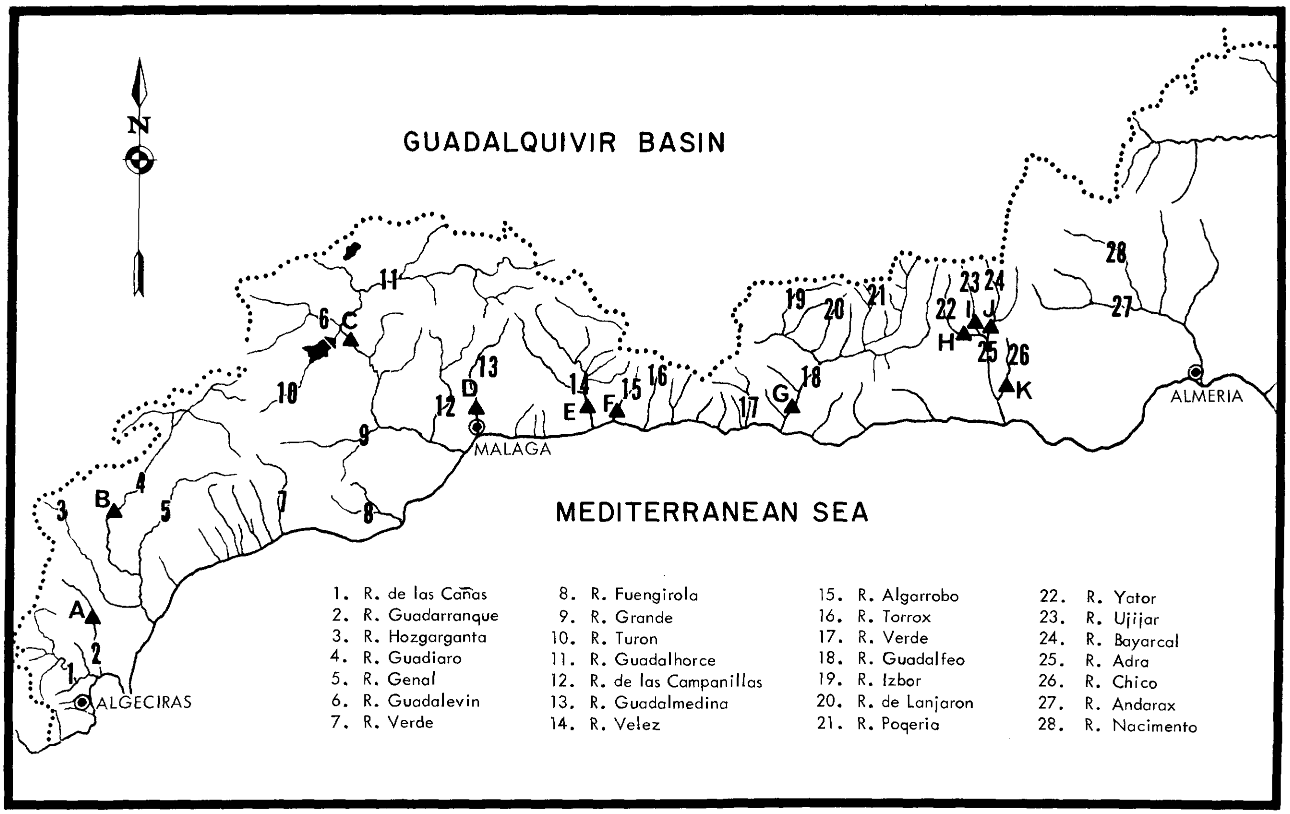


FIGURE 4.—Map showing distribution of rivers on the southern Iberian margin. (Black triangles denote stations occupied by the Centro de Estudios Hidrográficos (1966); river flow data listed in Table 3.)

and distinguish different types of feldspar grains. A total of about 300 light mineral grains and 200 transparent, heavy mineral grains were counted and relative percentages calculated. Opaque minerals were also counted. Mica flakes occur in both heavy and light mineral concentrations; in this study, the micas have been assigned for quantitative purposes to the light mineral fraction.

A total of 23 mineral species were identified in the heavy fractions, many of them occurring in trace amounts or in only a few samples. Only the dozen or so nonopaque mineral species which appear with reasonable consistency in a large number of samples have been distinguished and plotted in Figures 7 and 9. Moreover, for purposes of quantitative comparison the related mineral species have been grouped together in a manner reflecting their provenance characteristics and assigned to 10 categories (including opaque minerals and "others"). Similarly, light minerals were assigned to eight groups, together with two ratios (total quartz to total feldspar, and igneous quartz to metamorphic quartz). Certain categories of light minerals, notable rock fragments and glauconite, although locally common, are not sufficiently widespread in their occurrence to justify the erection of additional compositional groups.

Inspection of the compositional data from individual samples (Figures 7 to 10) revealed significant geographic variations, which enabled the Spanish and Moroccan samples to be assigned to provinces (i.e., regions characterized by sands of comparable composition). In most cases, the province boundaries can be drawn solely on the basis of marked changes in the relative abundance of several of the heavy or light mineral groups. However, in a few instances, there is a more gradual change in composition, and the province boundary is then more arbitrarily defined, usually on the basis of some geographic feature such as a major river or prominent cape.

This original compositional data was subsequently compared with data previously obtained from deep-sea samples in the Strait of Gibraltar

TABLE 2.—*Sediment sample localities on the northern Mediterranean coast of Morocco, from west to east* (see Figure 3)

SAMPLE NUMBER	MOROCCAN SAMPLE LOCALITY
M 8	Mouth of Oued el Herradou, approx. 4 km west of Tangier town center
M 1	Beach at mouth of Oued Chall, just east of Tangier
M 2	Oued approx. 4 km south of Cap Malabata on Route S704, about 2 km from coast
M 3	Beach at mouth of Oued Sfisifa, near Pointe Kankouch
M 4	Oued el Lgam, along Route S704, near Pointe Bou Maaza
M 5	Oued el Kazor, at Ksar-es-Seghir, along Route S704
M 6	Beach at Benzou, about 10 km west of Ceuta
M 7	Beach about 6 km southwest of Ceuta, near junction of Routes P28 and 8303
M 20	Small oued at Riffien, north of Oued Negron, Route P28
M 21	Mouth of Oued Negron, north of Restinga, Route P28
M 22	Dune sand in Restinga-Smir area, 16 km south of Ceuta, Route P28
M 19	Near mouth of Oued Smir, along Route P28, 3 km north of M'Diq
M 23	Oued ed Siador, along Route P28, 3 km south of Cabo Negro
M 9	Rio Martin, just south of Tetouan
M 18	Oued just north of Cap Mazari, approx. 13 km southeast of Tetouan, Route S608
M 17	Oued Emsa, south of Cap Mazari and west of Cap Timousourga, Route S608
M 16	Oued on southeast flank of Cap Akaili, Route S608
M 15	Oued northwest (approx. 4 km) of Cap Menkal, Route S608
M 14	Oued Laou, near Es Sebt, Route S608
M 13	Oued Akheron, near El Arba, Route S608
M 12	Mouth of Oued Targa, at Targa, Route S608
M 11	Oued, near Asenli, approx. 5 km southeast of Targa, Route S608
M 10	Junction of Oued el Had and Oued Bouchia at town of Bou-Hamed, Route S608
M 24	Mouth of Oued Ouringa, approx. 1 km west of Pointe des Pecheurs
M 25	Mouth of small Oued, Pointe des Pecheurs
M 28	Junction of Oued Mestasa and Oued Bi Chetouan, near village of Mastassa
M 27	Mouth of Oued 0.5 km east of Cala Iris beach
M 26	Mouth of Oued Bou Frah, near Torres-de-Alcala
M 29	Oued Bades, north of Arba-Snada, on Route S610
M 30	Oued approx. 4 km east of El Hader Rouadi, on Route S610
M 31	Oued Merelia, west of Ait-Kamara, on Route S610
M 35	Mouth of Oued Boussikour, approx. 12 km west of Al Hoceima
M 36	Oued east of Pointe Boussikour, approx. 7 km west of Al Hoceima
M 37	Small Oued approx. 3 km west of Al Hoceima, on Piste 8506
M 38	Beach below Mohammed V Hotel, Al Hoceima (no Oued)
M 34	Beach at Plage Espalmadero, 4.5 km southeast of Al Hoceima on Route P39A
M 33	Oued Rhis, approx. 12 km southeast of Al Hoceima, on Route P39
M 32	Oued Nekor, approx. 6 km south of Al Hoceima Bay, on Piste S604

TABLE 3.—*River flow data collected on the southern Iberian margin* (see Figure 4); *sample stations occupied by the Centro de Estudios Hidrográficos (1966)*

RIVER	SAMPLE STATION CODE (FIG. 4)	LITERS/SECOND	MONTHS DRY
Guadarranque	A	17.2	July, August
Guadiaro	B	19.4	July, August
Guadalhorce	C	4.73	None
Guadalmina	D	8.17	July, August
Velez	E	5.65	July, August (almost dry)
Algarrobo	F	5.49	June, July, August
Guadalfeo	G	3.47	August
Adra	H,I,J,K	2.13 (average)	July, August (almost dry)

region and the western Alboran Basin (Kelling and Stanley, 1972; Huang and Stanley, 1972), reassigned as far as possible to the same mineralogic groupings (Table 8).

A survey of selected aerial photographs, collected at altitudes of from 5,000 to 14,000 m, was made in order to provide information on short- and long-term coastal sedimentation and littoral drift patterns on both the Moroccan and Spanish margins. Predominant near-shore current drift paths (cf., Figures 12 to 14) are defined on the basis of beach-groin patterns, delta shapes and river outflow, and suspended sediment lobe distribution. Particular attention has also been paid to published data of river flow and rain data (cf., Figures 4 and 20) on the Spanish margin (Centro de Estudios Hidrográficos, 1966, 1970) and to offshore surface drift data in the Alboran Sea (Gaibar-Puertas, 1967; Lanoix, 1974).

Definition of Mineralogic Provinces

GENERAL

Both heavy and light minerals are utilized in defining the various mineralogic provinces in the study area. The light mineral fraction in the very fine to fine sand-size range accounts for the bulk (usually 90 to 95% or more) of the total material present. In most instances, approximately 2 to 11 samples comprise the regional mean.

Thirteen zones have been established on the southern Iberian margin between Tarifa and Adra and seven on the Moroccan coast from Cap Spartel to the mouth of the Oued Nekor. In addition, assemblages already established for the sublittoral portions of the Strait of Gibraltar Submarine Valley and the Western Alboran Basin (Kelling and Stanley, 1972a, b; Huang and Stanley, 1972) were reexamined in the light of this new data.

The abundance of individual light and heavy mineral species may differ appreciably from sample to sample (see Figures 7 to 10), but it is seldom feasible to utilize the presence or absence of specific minerals to define geographic associations. We have found it more useful to assign the dominant heavy mineral species to ten groups (cf., Tables 5, 7, and 8), which are defined primarily on the basis of probable provenance. Seven light mineral groups are recognized in this study. In addition, two compositional ratios (igneous quartz/metamorphic quartz and total quartz/feldspar) help define mineralogic provinces.

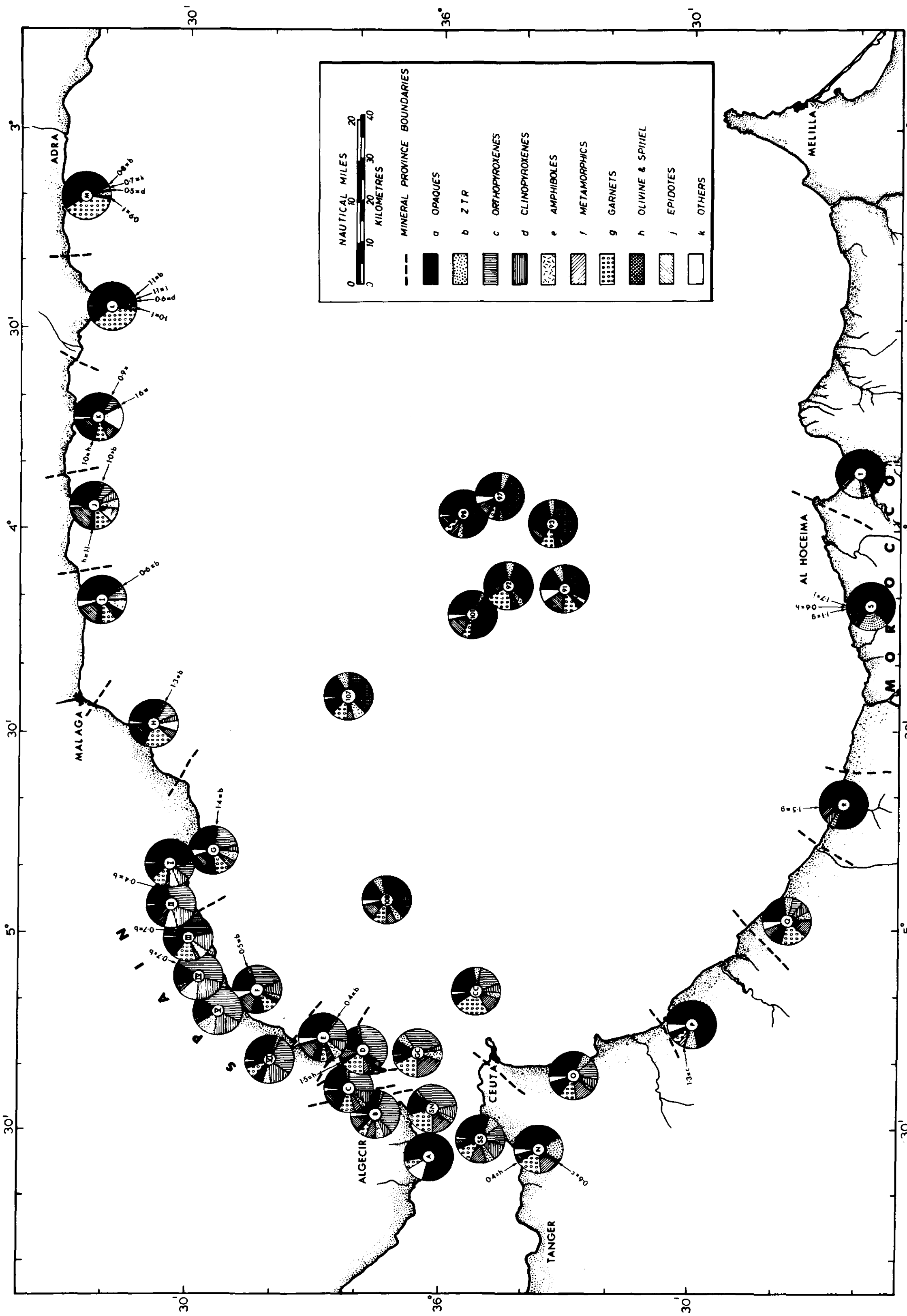


FIGURE 5.—Heavy mineral data in the Alboran Sea-Strait of Gibraltar region summarized in the form of pie diagrams. (Dashed lines denote mineral province boundaries. Data listed in Tables 5–8.)

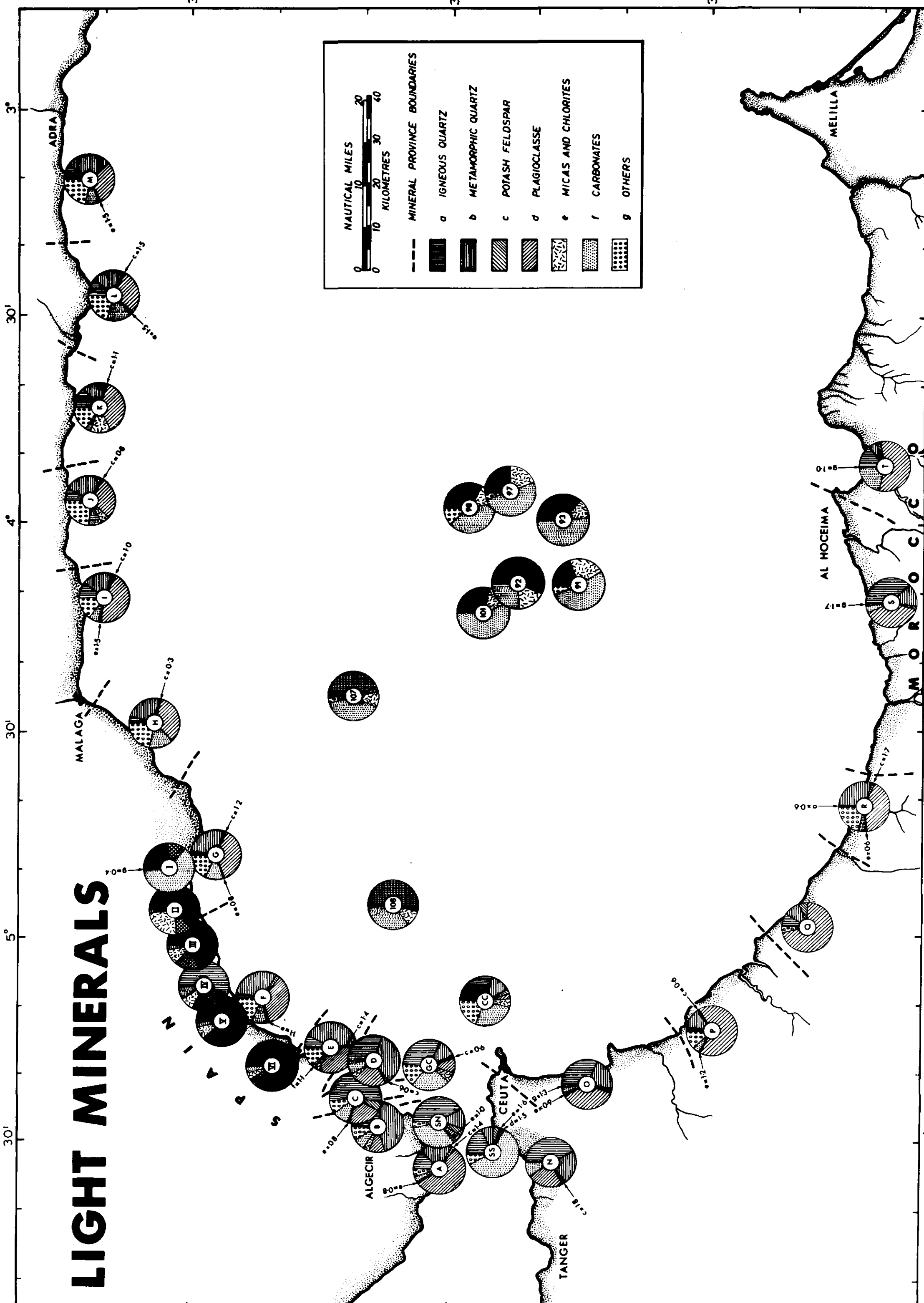


FIGURE 6.—Light mineral data in the Alboran Sea–Strait of Gibraltar region summarized in the form of pie diagrams. (Dashed lines denote mineral province boundaries. Data listed in Tables 5–8.)

TABLE 4.—*Mineral provinces for Spanish coastal and river samples* (see Figures 5 to 8)

Province Designation	Geographic Limits of Province	Sample Numbers	Remarks
	COASTAL	SAMPLES	
A	Tarifa to Punta San García (Algeciras Bay)	S1,2,6,7,8	No heavy mineral fractions from sample S6
B	Punta San García (north side) to Río Guadarranque mouth	S9-13	
C	Río Guadarranque mouth to Europa Point, Gibraltar	S14-16, G4	
D	Europa Point, Gibraltar (east side) to La Línea (eastern beach)	G1,2,3,5; S19	
E	La Línea to Guadiaro River mouth	S20-23	
F	Guadiaro River mouth to Río Verde mouth (Marbella)	S24-36	No heavy mineral fractions from samples S25, 28, 30
G	Río Verde mouth to Torrente Calaburra	S37-43	
H	Torrente Calaburra to Rio Guadalhorce mouth (Málaga)	S44-50	
I	Río Guadalhorce mouth to Río Vélez mouth	S51-60	
J	Río Velez mouth to Río Higuerón mouth (Nerja)	S61-70	No heavy mineral fractions from samples S62, 67
K	Río Higuerón mouth to Río Guadalfeo delta	S71-74,76,78-81	
L	Río Guadalfeo delta to Calahonda	S82-91,93	No heavy mineral fractions from samples S82,90-93
M	Calahonda to Adra	S94-104	No heavy mineral fractions from samples S96,101,104
	RIVER	SAMPLES	
I	Río de Calena	IA, IB	
II	Río Guadaiza	IIA, IIB	
III	Río Guadalmansa	IIIA, IIIB	
IV/V	Río Padrón and Rio Enmedia	IVA, IVB, VA, VB	
VI	Río Guadiaro-Genal	VIA, VIB	

Province boundaries were established primarily on the basis of marked changes in either qualitative or quantitative character of the mineral content of the samples, and were further defined in light of geographic factors (presence of major rivers, promontories and capes, etc.).

Spanish River Samples

The river samples constitute five associations which are distinguishable on both heavy and light mineral components (Figures 5 and 6). These will be discussed in sequence from west to east.

GUADIARO-GENAL ASSEMBLAGE (VI).—This heavy mineral suite is characterized by moderate amounts of orthopyroxene and clinopyroxene, together with a relatively high proportion of metamorphic group minerals (mainly andalusite) and opaque grains. The content of ZTR (zircon, tourmaline, rutile) is higher than in any other Spanish rivers. The total quartz abundance also attains its highest value in this river, while total feldspar is present in minimal quantities.

ENMEDIA-PADRÓN ASSEMBLAGE (IV–V).—These two rivers furnish closely similar, heavy mineral assemblages which display the highest values of orthopyroxenes, clinopyroxenes, and amphiboles encountered in the Spanish rivers and exceeded by only two coastal samples. Opaque grains and the ZTR group are deficient. There is a more conspicuous difference between the two rivers in terms of light minerals, the Enmedia being substantially richer in quartz and poorer in feldspar content than the Padrón.

GUADALMANSA ASSEMBLAGE (III).—This assemblage is distinguished from the neighboring rivers on the basis of its greatly enhanced garnet and olivine plus spinel. The light mineral assemblage is broadly similar to that of the Padrón River.

GUADAIZA ASSEMBLAGE (II).—The heavy mineral assemblage is distinguished by the highest proportions of metamorphic group minerals (mainly staurolite), olivine and spinel, and contains the lowest proportions of garnet. The light mineral assemblage is characterized by a high quartz to feldspar ratio, together with a greatly increased content of mica.

RÍO DE CALENA ASSEMBLAGE (I).—This assemblage is notably deficient in pyroxenes and amphiboles but relatively enriched in opaque minerals and garnet. Carbonate minerals predominate in the light mineral assemblage, but quartz substantially exceeds feldspars in abundance.

IBERIAN COAST

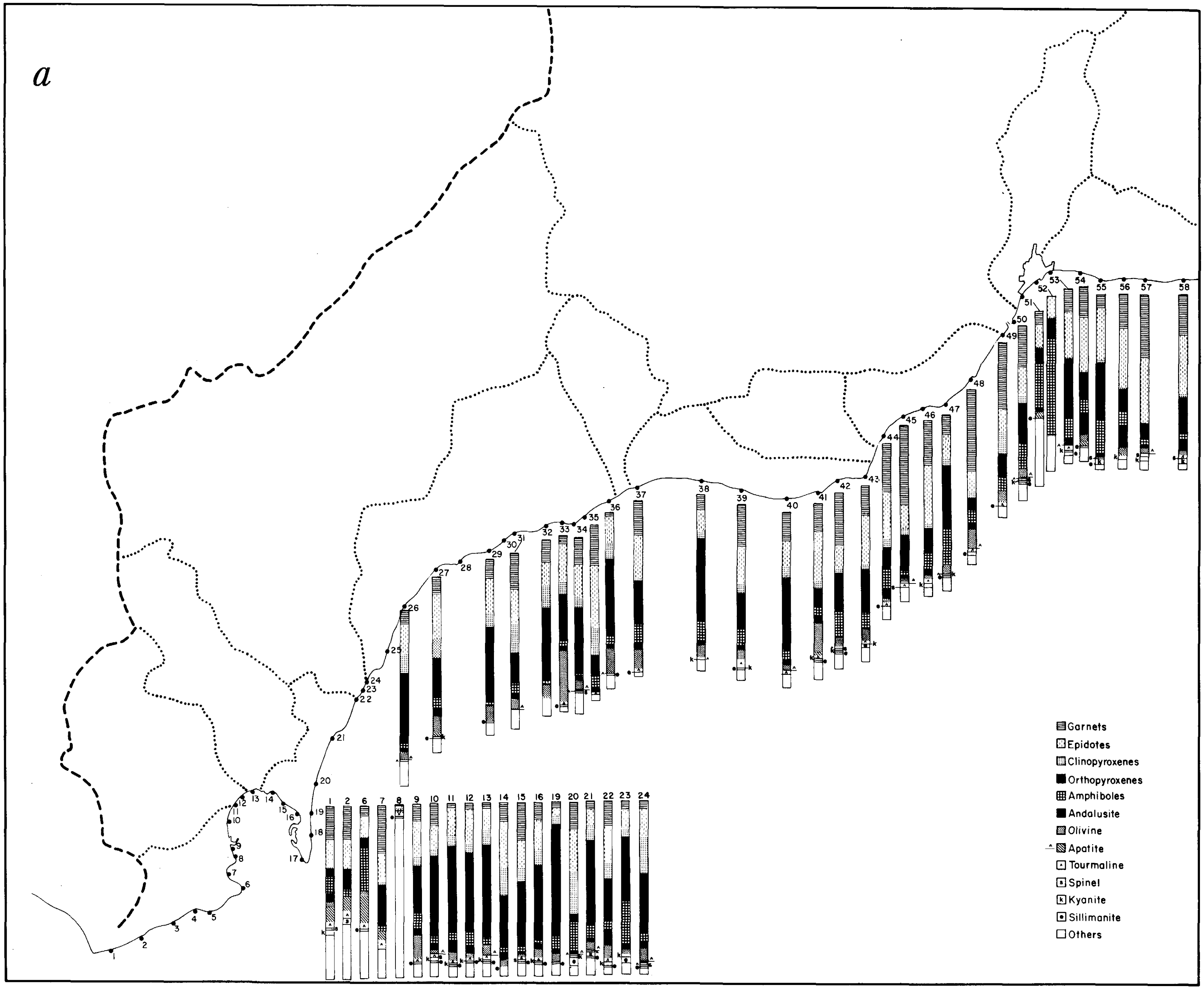
PROVINCE A.—This province extends from Tarifa to Punta San García, in the southwest part of Algeciras Bay (Figures 7 and 8). No major rivers traverse this rocky coast. The heavy assemblage is dominated by the opaque minerals, although the proportion of ZTR minerals reaches its maximum for the Iberian coastal samples. The percentage of opaque and ZTR minerals increases eastward, whereas that of garnet, epidote, and olivine actually decreases. All other heavy mineral groups are equally deficient. The total content of quartz is comparable to values obtained in other samples from the southern Iberian margin but considerably lower than the immediately adjacent provinces. However, the ratio of igneous to metamorphic quartz is comparable to that measured in the neighboring regions. The total feldspar percentage for this province reaches a maximum for these Iberian samples, and as a consequence the quartz/feldspar ratio is minimal.

PROVINCE B.—This province includes samples on the west side of Algeciras Bay, from Algeciras to the mouth of the Río Guadarranque. The major rivers are the Palmones and Guadarranque. The heavy assemblage is characterized by a reduced proportion of opaque minerals and a greatly enhanced content of pyroxenes. The opaque minerals

TABLE 5.—*Mineralogic composition of Spanish coastal and river samples–province means* (see Figures 5 and 6)

	PROVINCE	A	B	C	D	E	F	G	H	I	J	K	L	M	I	II	III	IV	V	VI
HEAVY MINERALS	Opaque Minerals	79.9	25.6	21.6	19.0	33.9	17.1	27.0	30.3	42.6	30.0	29.9	39.7	43.4	46.5	20.4	11.0	7.5	10.8	28.5
	Zircon + Tourmaline + Rutile (ZTR)	2.3	1.3	1.5	tr.[5]	tr.	0.5	1.4	1.3	0.6	1.0	0.9	1.1	0.8	1.7	tr.	0.7	0.7	-	2.3
	Orthopyroxenes	2.5	34.2	27.8	38.6	18.4	26.9	20.0	12.7	10.5	9.1	8.9	1.1	0.7	10.9	33.4	32.5	44.2	45.5	30.0
	Clinopyroxenes	0.5	4.8	8.3	6.5	8.9	10.3	3.2	3.8	0.6	5.6	1.6	0.6	0.5	5.8	4.5	13.6	21.1	19.2	12.8
	Amphiboles	1.9	5.0	3.2	2.4	8.7	3.9	7.4	7.5	9.4	8.3	18.0	4.1	3.2	5.8	7.1	7.2	13.6	12.8	5.2
	Metamorphic Group[1]	1.0	5.1	4.4	4.8	5.1	2.7	3.2	3.0	5.0	9.0	7.9	1.0	0.9	3.2	7.7	2.2	1.1	2.2	6.9
	Garnets	5.0	4.7	12.6	15.6	7.3	9.7	11.5	22.8	9.9	11.5	6.4	40.6	38.6	13.8	0.8	16.1	2.8	2.8	7.3
	Olivine + Spinel	0.7	3.7	2.3	1.5	2.6	7.5	5.6	3.1	1.2	1.1	1.0	2.0	1.0	8.7	10.1	12.4	6.7	4.8	3.2
	Epidote Group	3.6	12.5	15.1	9.7	11.4	16.7	14.9	12.8	17.4	22.6	22.5	8.9	8.1	1.8	4.7	2.8	2.3	1.4	1.1
	Others[2]	2.6	3.1	3.2	1.6	3.3	4.7	5.8	2.7	2.8	1.8	1.9	0.9	2.8	1.8	0.9	1.5	-	1.9	2.7
LIGHT MINERALS	Igneous Quartz[3]	12.1	25.2	20.6	29.6	8.1	2.8	2.4	4.2	10.9	7.8	14.2	10.8	9.7						
	Metamorphic Quartz[4]	19.7	45.7	31.5	33.3	41.5	31.7	28.5	22.8	21.3	25.4	15.0	20.0	30.3						
	Total Quartz	31.8	70.9	52.1	62.9	49.6	34.5	30.9	27.0	32.2	33.2	29.2	30.8	40.0	24.5	62.0	60.5	54.6	79.5	85.7
	Igneous/Metam. Quartz Ratio	0.61	0.55	0.65	0.88	0.19	0.08	0.08	0.18	0.51	0.30	0.94	0.54	0.32						
	Potash Feldspar	1.4	-	8.1	0.6	1.4	2.6	1.2	tr.	1.0	0.8	1.1	1.5	tr.						
	Plagioclase	56.0	10.0	22.6	21.2	30.1	34.1	37.9	37.0	43.0	28.8	38.2	29.2	28.0						
	Total Feldspar	57.4	10.0	30.7	21.8	31.5	36.7	38.1	37.3	44.0	29.6	39.3	30.7	28.4	8.5	9.5	15.3	24.6	8.4	3.5
	Quartz/Feldspar Ratio	0.55	7.09	1.69	2.88	1.57	0.94	0.81	0.72	0.73	1.12	0.74	1.00	1.40	2.88	6.53	4.54	2.22	9.46	24.5
	Micas + Chlorite	0.8	3.9	0.8	2.7	1.1	1.3	0.8	-	1.5	5.5	11.8	1.7	1.5	3.0	26.5	12.1	10.5	8.0	6.3
	Carbonates	4.4	5.7	10.7	7.0	4.5	9.6	12.2	14.6	6.9	8.1	3.5	18.5	7.9	64.0	2.0	3.1	11.0	4.0	4.1
	Others[6]	5.3	9.2	5.7	5.6	13.0	17.6	17.7	20.0	14.6	24.0	16.1	18.0	22.0						
	NO. OF SAMPLES	4/3[7]	5/1	4/2	5/4	4/1	10/2	7/2	7/1	10/5	8/2	9/1	7/2	8/2	2/2	2/2	2/2	2/2	2/2	2/2

1. Comprises Kyanite, Staurolite, Sillimanite, Andalusite and Chiastolite
2. Mainly Apatite, Sphene, Anatase, Monazite, Corundum and Topaz
3. Simple, unstrained quartz
4. Composite and strained quartz
5. tr. = trace (< 0.5%)
6. Mainly rock-fragments, carbonaceous debris and glauconite
7. First digit refers to number of samples averaged for heavy minerals; second digit refers to number of samples averaged for light minerals.


a
Garnets
Epidotes
Clinopyroxenes
Orthopyroxenes
Amphiboles
Andalusite
Olivine
Apatite
Tourmaline
Spinel
Kyanite
Sillimanite
Others

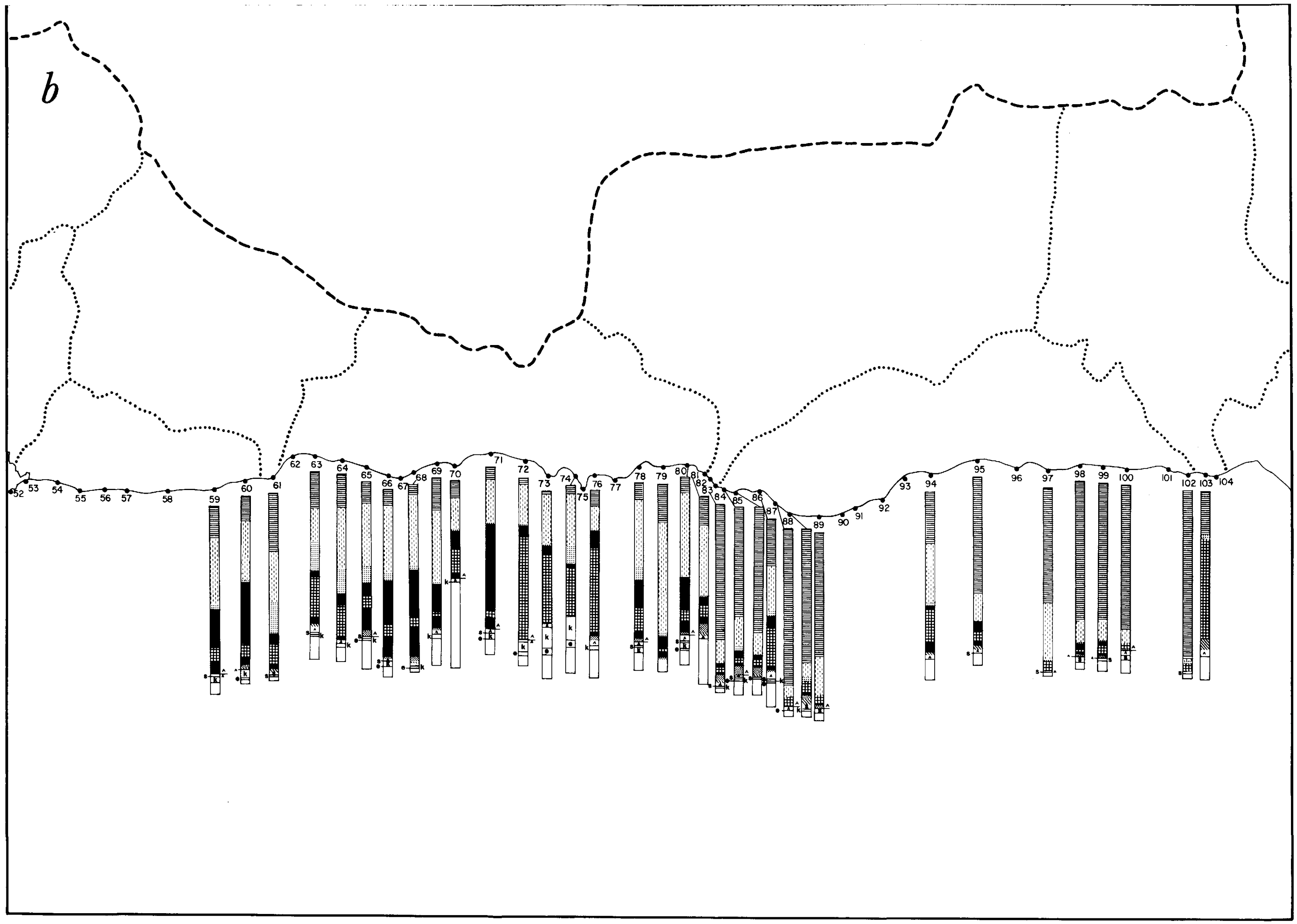
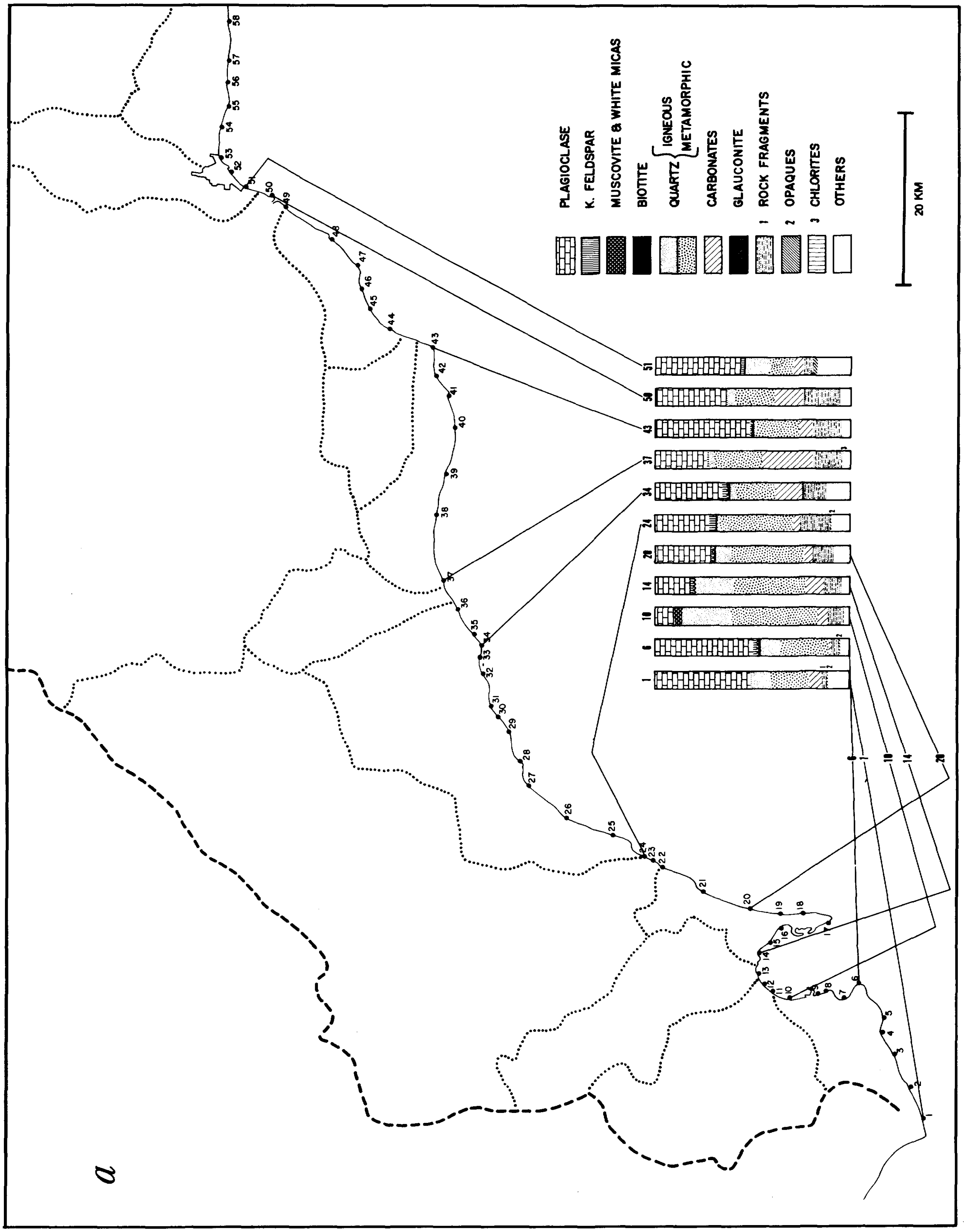


Figure 7.—Bar diagrams showing the relative percentages of transparent heavy minerals on the southern Iberian margin.


PLAGIOCLASE
K. FELDSPAR
MUSCOVITE & WHITE MICAS
BIOTITE
QUARTZ IGNEOUS METAMORPHIC
CARBONATES
GLAUCONITE
1 ROCK FRAGMENTS
2 OPAQUES
3 CHLORITES
OTHERS
20 KM
a

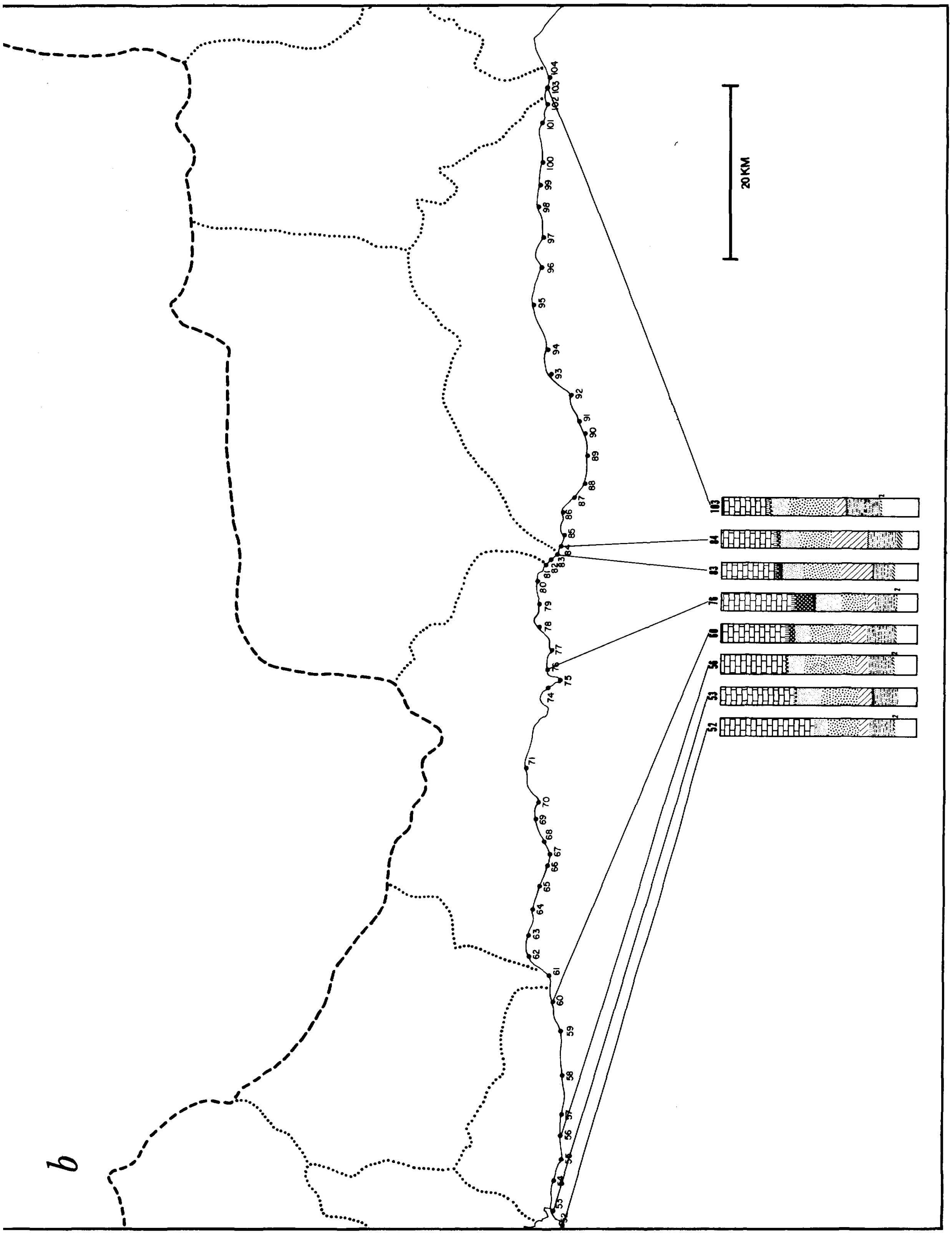


FIGURE 8.—Bar diagrams showing the relative percentages of principal light minerals on the southern Iberian margin.

decrease northward paralleling the increase of pyroxenes. The light assemblage comprises the highest total quartz, the lowest amounts of feldspar, and one of the higher proportions of micas encountered in the southern Iberian coastal samples.

PROVINCE C.—This province extends from northern Algeciras Bay near Arroyo de los Lecheros to Europa Point on the southern tip of Gibraltar. There are no major rivers in this region. The heavy assemblage includes enhanced proportions of garnet and clinopyroxene and slightly higher epidote. The southernmost sample (G4) is somewhat anomalous in this group, displaying a considerably increased quantity of opaque and ZTR minerals and a deficiency of ferromagnesian minerals. There is a slight decrease in clinopyroxenes toward the south, whereas the orthopyroxenes increase as far as La Línea. The light assemblage is characterized by the highest proportion of potash feldspar sampled anywhere on the Iberian coast. The proportion of total quartz, although less than adjacent provinces, is still relatively high, and the igneous to metamorphic quartz ratio is similar to that of provinces A and B. Mica content is diminished.

PROVINCE D.—This province lies on the eastern flank of Gibraltar from Sandy Bay to La Línea. There are no rivers in this region. The heavy fraction is distinguished by the highest mean value of orthopyroxene encountered in the coastal samples. Epidotes show a regular decrease northward as far as La Línea, and garnet increases northward to a maximum near the Gibraltar airfield and then declines. Quartz dominates the light mineral assemblage with the second highest mean value of Iberian coastal samples measured. Metamorphic quartz exceeds igneous quartz. The total amount of quartz decreases rather steadily from this province eastward as far as Province H, while the total feldspar content displays a corresponding increase.

PROVINCE E.—This province extends from north of La Línea to the mouth of the Guadiaro River, the only major river in this sector. The heavy fraction in this province contains somewhat enriched opaque minerals, amphiboles, and metamorphics, together with diminished amounts of orthopyroxenes. There is a notable increase in the proportion of opaques northward, accompanied by a decrease in clinopyroxenes. The proportion of quartz with respect to feldspar is diminished, and the igneous to metamorphic quartz ratio is substantially reduced compared to the previously described provinces.

PROVINCE F.—This province extends from north of the mouth of the Guadiaro River to near the mouth of the Río Verde west of Marbella. This sector includes numerous other rivers, such as the Manilva, Padrón, Guadalmansa, Guadalmina, and Guadaiza. The heavy assemblage is distinguished by the highest mean values of clinopyroxene and olivine with spinel and the lowest values of opaque minerals. Amphiboles and metamorphic minerals are somewhat diminished with respect to the adjacent provinces. There is a general increase in opaque minerals toward the northeast. The highest value of olivine in the Iberian coastal samples occurs at the mouth of Arroyo dos Hermanas (sample 33). There is an irregular decrease northward in proportion of clinopyroxenes. The decline in the total quartz content observed in Province E is continued into Province F and is accompanied by a corresponding increase in the total amount of feldspar (largely plagioclase), which in fact slightly predominates. Curiously, the ratio of igneous to metamorphic quartz reaches a minimum value in Provinces F and G.

PROVINCE G.—This province extends from 3 km west of Marbella to the Torrente Calaburra. Rivers include the Arroyo de Calena, Río Real, Arroyo de Siete Revueltas, and Arroyo de Cala del Moral. The heavy fraction is distinguished by a slightly enhanced proportion of opaque and ZTR minerals and a decreased amount of pyroxenes. There is an irregular increase in garnet toward the east. The light fraction is broadly similar to that in Province F, but it has a slightly higher proportion of feldspar to quartz and a higher proportion of detrital carbonate.

PROVINCE H.—This province extends from the Río Fuengirola to the Guadalhorce River, west of Málaga, the major river in this sector. The heavy fraction is distinguished by an enhanced proportion of garnet and diminished pyroxene and olivine content. There is an irregular decrease in metamorphic minerals toward the northeast. The total quartz reaches a minimal value for the coastal samples, whereas the total feldspar content is comparable to that of Province G. The proportion of detrital carbonate is again increased.

PROVINCE I.—This province extends from west of

Málaga to west of the Río Velez. The Guadalmedina is the most important river in this sector. The heavy fraction is distinguished by high mean proportions of opaque minerals and epidotes and decreased amounts of pyroxene (especially clinopyroxene) and garnet. Very high values of amphiboles are localized at the mouth of the Guadalmedina River and beach to the southwest (samples 52 and 51). There is an increase in epidote eastward toward Estación Benagalbón. The light assemblage has the second highest total feldspar content and a somewhat enhanced proportion of igneous quartz.

PROVINCE J.—This province extends from the mouth of the Río Vélez to the mouth of the Río Higuerón. Important rivers include the Vélez, Algarrobo, Torrox, and Chillar. The heavy fraction includes somewhat enhanced proportions of clinopyroxene, metamorphic group minerals, and epidote. There is a slight but regular decrease in the opaque minerals eastward. There is also a marked and regular decrease in amphiboles eastward from east of the Río Vélez delta, but a notable increase in amphibole is observed at the mouth of the Río Chillar. The total quartz content and the ratio of igneous to metamorphic quartz are similar to values encountered in Province I, but the total feldspar content is substantially reduced. The percentage of micas and chlorite also increases significantly with respect to Province I.

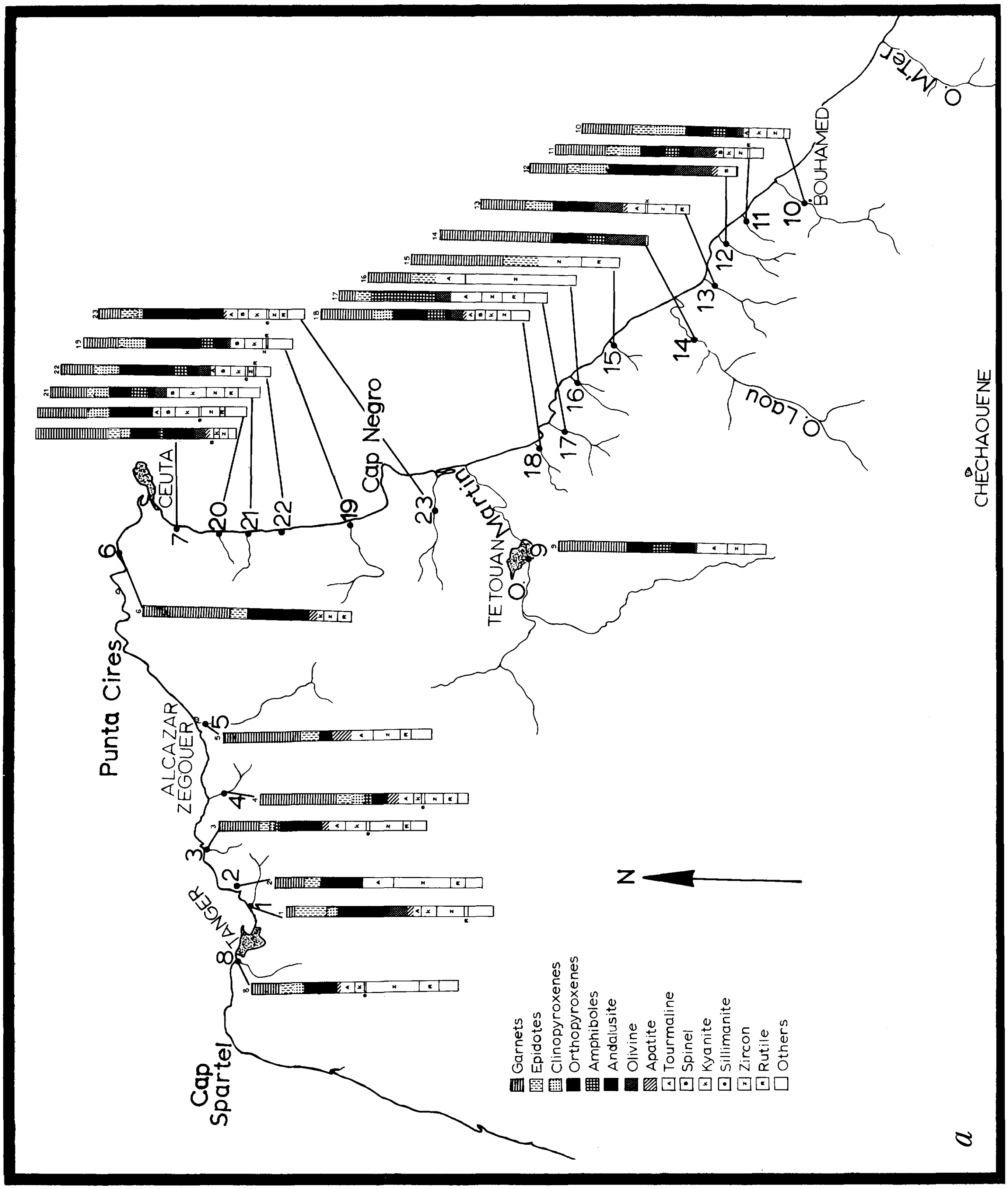
PROVINCE K.—This province extends from east of Nerja to west of the mouth of the Río Guadalfeo. The Río Verde is the most important river in this sector. The heavies are characterized by a marked increase in the amphibole content and decrease in the clinopyroxene and garnet. The proportions of amphiboles are substantially higher in the samples west of the Río Verde (nos. 72–76), whereas the proportions of opaque minerals and epidotes are substantially greater to the east of the Río Verde. In the light fraction, the total quartz content remains relatively low, although it is noteworthy that the proportions of igneous and metamorphic quartz are nearly identical in sharp contrast to adjacent provinces. The highest values of micas and chlorite in the Iberian coastal samples occur in this province.

PROVINCE L.—This province extends from the delta of the Río Guadalfeo to west of Calahonda. The Guadalfeo is the only major river in this sector. The heavy fraction is dominated by garnet, and there is a decrease in almost all other mineral groups except the opaques. The major break in trend of proportion of garnet occurs on both sides of the mouth of the Guadalfeo. The proportion of epidote also decreases noticeably east of the mouth of the Guadalfeo. It is noteworthy that in the region of El Varadero (sample 86), there is a dramatic change in the amphibole and epidote content and a corresponding decrease in garnet. The light assemblage is essentially similar to Province K except that the proportion of metamorphic quartz is again higher, while the micas and chlorite revert to a low value. The carbonate content is also substantially higher than in the neighboring provinces.

PROVINCE M.—This province extends from Castell de Ferro to east of Adra. The major river is the Chico (Río Adra). The heavy assemblage is distinguished by garnet and opaques and a slightly diminished olivine content. Garnet content increases toward the east from Punta Negra, and the epidote decreases eastward from this point as well. The major break in mineral trends is localized at the delta of the Río Chico, just west of its mouth, where proportion of amphiboles and opaque minerals increase substantially, accompanied by a very marked decrease in garnet content. The light fraction is marked by a substantial increase in total quartz content and a slight decrease in total feldspar and micas. The proportion of detrital carbonates is also significantly reduced compared with Province L.

MOROCCAN MARGIN

PROVINCE N.—The area included in this province extends from Cap Spartel west of Tangier to west of Ceuta along the south flank of the Strait of Gibraltar (Figures 9 and 10). As in all seven Moroccan provinces, opaque grains comprise the most abundant single group of the heavy minerals. The ZTR group is dominant among the nonopaque minerals, closely followed by garnet and the metamorphic group. The proportion of garnet increases toward the east, while zircon tends to decrease in the same direction. Significantly, orthopyroxene and olivine occur only in the beach samples from the western sector of the Strait. Andalusite is the dominant metamorphic mineral, but


Cap Spartel
TANGER
ALCAZAR ZEGOUER
Punta Cires
CEUTA
Cap Negro
TETOUAN
O. Martin
O. Laou
CHECHAOUENE
BOUHAMED
O. M'ter
N
Garnets
Epidotes
Clinopyroxenes
Orthopyroxenes
Amphiboles
Andalusite
Olivine
Apatite
Tourmaline
Spinel
Kyanite
Sillimanite
Zircon
Rutile
Others
a

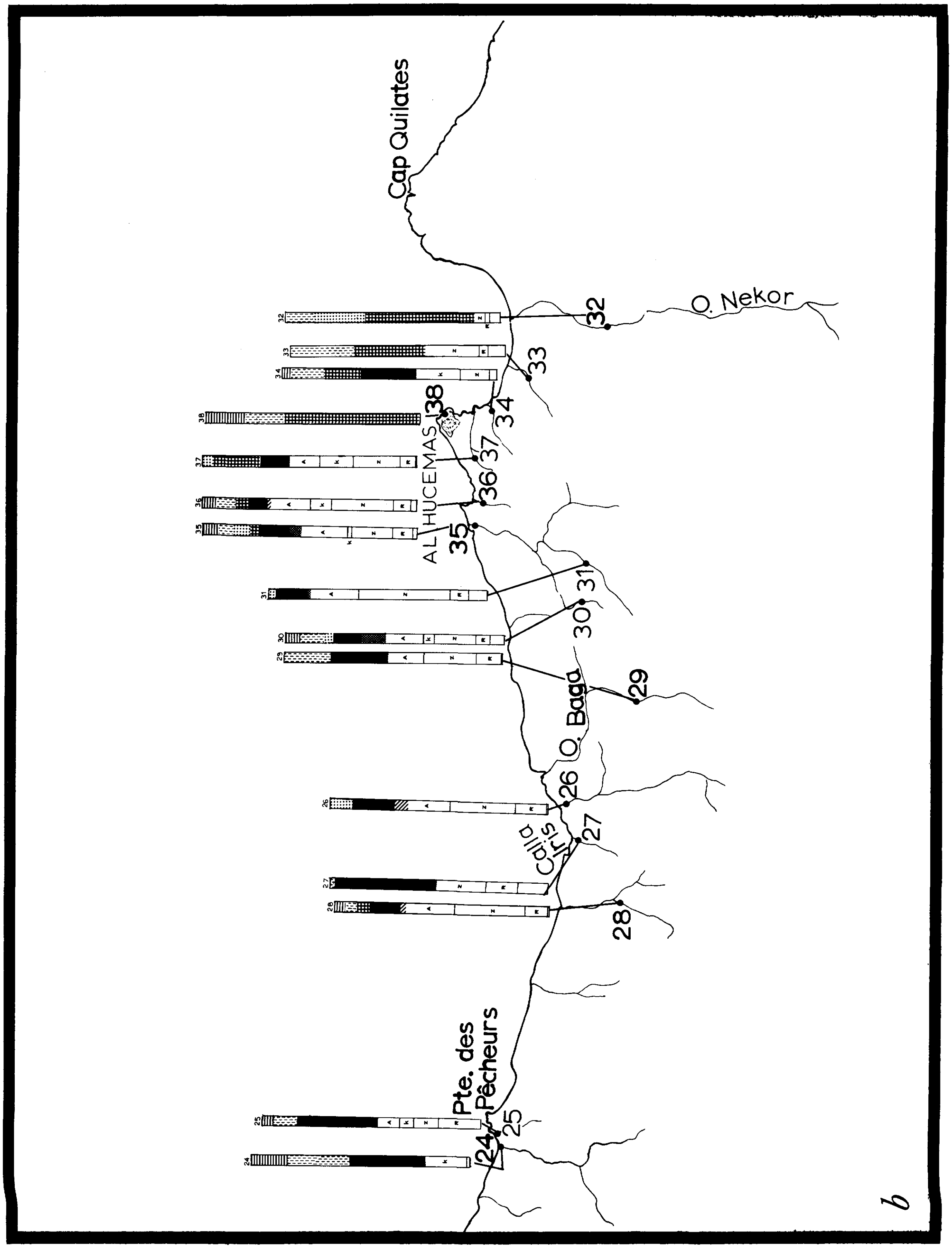


FIGURE 9.—Bar diagrams showing the relative percentages of transparent heavy minerals on the northern Moroccan margin.

staurolite also occurs in all samples. Dolomite rhombs are abundant in samples M8 (west of Tangier) and M6 (below Djebel Moussa near Ceuta). Quartz dominates the light mineral assemblage with the igneous variety generally in excess of metamorphic quartz. The average total feldspar content is the lowest observed in the Moroccan samples.

PROVINCE O.—This province extends from the south side of Ceuta peninsula to Cap Mazari. The major river in this sector is the Río Martin. This association contains substantially higher propor-

TABLE 6.—*Mineral provinces for Moroccan coastal and river samples* (see Figures 5, 6, 9, 10)

Province Designation	Geographic Limits of Province	Sample Numbers	Remarks
N	Cap Spartel to Ceuta (north side)	M1-6,8	M1,3,6,8 are coastal samples.
O	Ceuta (south side) to Cap Mazari	M7,9,18-23	M7,19,20-22 are coastal samples
P	Cap Mazari (south side) to Targa	M12-17	
Q	Targa to Bou Hamed (Oued El Had)	M10,11	
R	Oued Ouringa mouth to Pointe des Pecheurs	M24,25	M24 is a coastal sample
S	Oued Mestasa to Al Hoceima (western side)	M26-31, 35-37	M35 is a coastal sample
T	Al Hoceima (eastern side) to Oued Nekor	M32-34, 38	M38 is a coastal sample

TABLE 7.—*Mineralogic composition of Moroccan samples–province means* (see Figures 5 and 6)

	PROVINCE	N	O	P	Q	R	S	T
HEAVY MINERALS	Opaque Minerals	41.3	29.1	70.2	22.9	80.0	63.1	63.6
	Zircon + Tourmaline + Rutile (ZTR)	18.4	5.8	8.1	5.7	3.6	20.8	4.5
	Orthopyroxenes	0.6	15.1	1.3	9.2	tr.	tr.	-
	Clinopyroxenes	tr.[5]	5.8	tr.	8.0	4.9	1.0	3.0
	Amphiboles	tr.	2.3	tr.	4.6	-	2.0	15.2
	Metamorphic Group[1]	13.8	15.1	4.0	12.6	8.3	10.9	4.5
	Garnets	17.2	13.9	6.7	18.4	1.5	1.1	1.5
	Olivine + Spinel	tr.	8.1	2.7	9.2	-	0.6	-
	Epidote Group	3.9	2.2	1.8	6.1	3.1	1.7	6.2
	Others[2]	3.9	2.6	4.9	4.3	-	-	1.5
LIGHT MINERALS	Igneous Quartz[3]	43.4	32.2	3.7	7.8	0.5	37.9	14.1
	Metamorphic Quartz[4]	22.6	19.5	13.8	11.7	29.3	13.6	6.1
	Total Quartz	66.1	51.8	17.5	19.5	29.8	51.5	20.2
	Igneous/Metam. Quartz Ratio	1.92	1.65	0.26	0.67	0.01	2.79	2.31
	Potash Feldspar	1.8	2.7	0.6	4.7	1.7	1.9	2.1
	Plagioclase	23.2	37.1	65.8	71.2	43.3	41.2	54.1
	Total Feldspar	25.0	39.8	66.4	75.0	45.0	42.1	56.3
	Quartz/Feldspar Ratio	2.64	1.30	0.26	0.26	0.66	1.22	0.36
	Micas + Chlorite	tr.[5]	0.9	1.2	tr.	0.5	tr.	0.5
	Carbonates	8.0	6.2	4.4	tr.	4.7	4.5	22.0
	Others[6]	tr.	1.3	9.5	5.0	19.9	1.7	1.0
	NO. OF SAMPLES	7	8	6	2	2	9	4

1. Comprises Kyanite, Staurolite, Sillimanite, Andalusite and Chiastolite
2. Mainly Apatite, Sphene, Anatase, Monazite, Corundum, Topaz
3. Simple, unstrained quartz
4. Composite and strained quartz
5. tr. = trace (< 0.5%)
6. Mainly rock-fragments and carbonaceous debris

tions of orthopyroxenes, clinopyroxenes, olivine, spinel and amphibole, and diminished ZTR and garnet. Amphiboles increase toward the south, while the metamorphic species decrease toward the south. A high proportion of dolomite rhombs occurs in sample M9 from the Río Martin. Feldspar increases in relation to quartz, and there is a slightly higher proportion of metamorphic quartz.

PROVINCE P.—This province extends from the south side of Cap Mazari to Targa. Important rivers in this region include Oued Emsa and Oued Laou. This region is characterized by an abundance of opaque and ZTR minerals. Both olivines and pyroxenes increase in the southern samples. High proportions of dolomite rhombs occur in sample M16 (near Cap Akaili) and M14 (Oued Laou). The total quartz content is minimal in samples taken north of the Oued Laou, while feldspar reaches a maximum value in the same samples. The ratio of igneous to metamorphic quartz increases substantially to the south of the Oued Laou.

PROVINCE Q.—This province extends from Targa to Bou Hamed and includes the Oued el Had. The heavy mineral assemblage here is similar to that of Province O, but it includes a slightly decreased proportion of orthopyroxene and increased amount of garnet. Olivines and both pyroxenes tend to increase northward. There is a dominance of the metamorphic quartz variety, and the ratio of quartz to feldspar is similar to that in Province P.

PROVINCE R.—This province includes the region adjacent to Pointe des Pêcheurs and includes the Oued Ouringa. The heavy mineral assemblage contains the highest proportion of opaque grains in the Moroccan samples. The metamorphic minerals (especially andalusite and kyanite) represent the most abundant nonopaque group. Orthopyroxenes, garnets, and olivines are notably deficient. Samples 24 and 25 contain high proportions of rhombic dolomite. The ratio of igneous to metamorphic quartz decreases considerably from that of Province Q, and the ratio of quartz to feldspar increases as a result of a significant diminution in the total feldspar content as compared with Province Q.

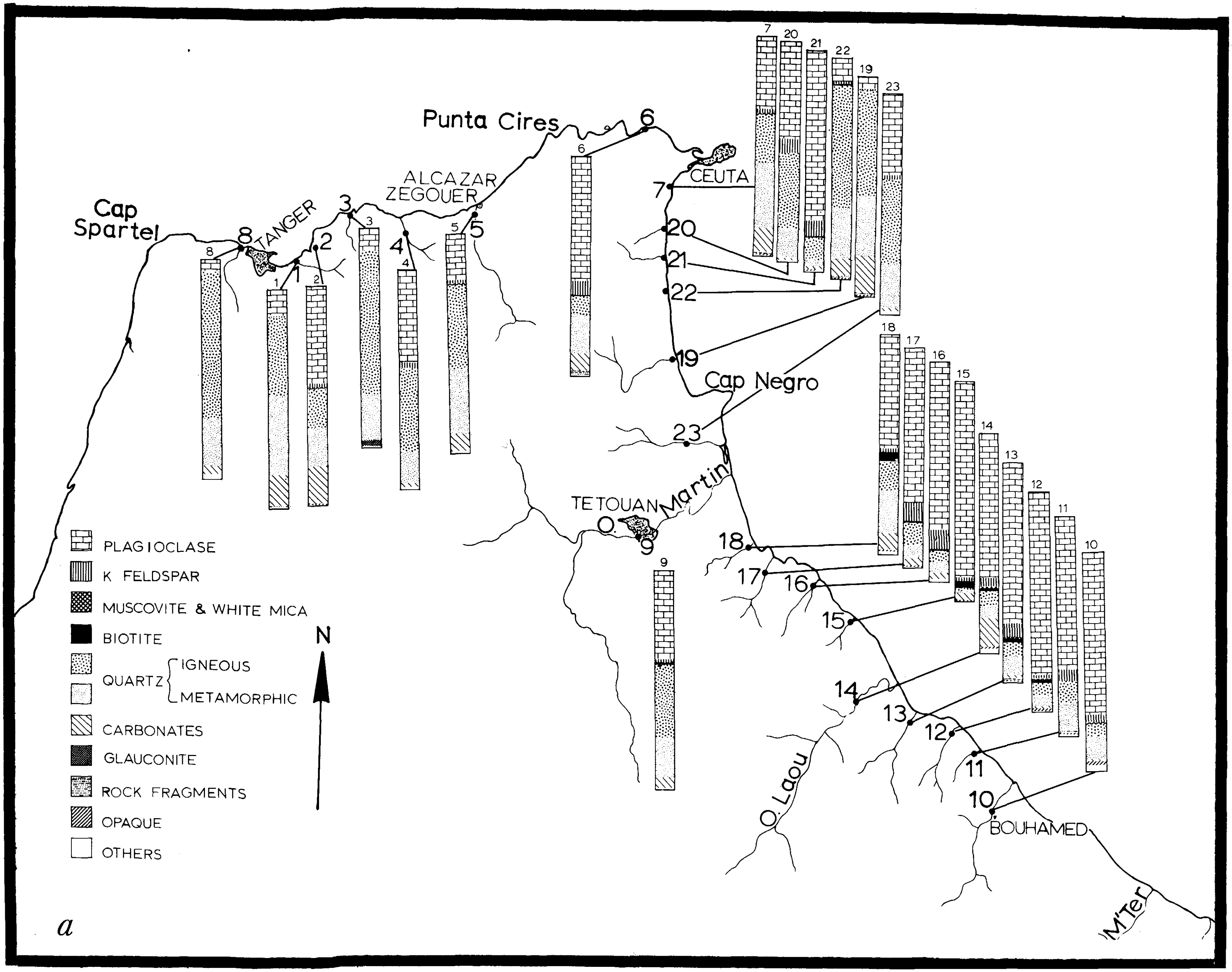
PROVINCE S.—This province extends from Oued Mastasa to just west of Al Hoceima (Al Hucemas). The most important rivers include the Oued Mastasa, Oued Bou Frah, Oued Bades, and Oued Boussikour. The dominant nonopaque heavy mineral group is the ZTR suite, which here attains its maximum abundance for Moroccan samples, especially in the Bou Frah-Mestasa drainage basin. The metamorphic minerals are also important, especially andalusite. Amphiboles are also present and increase conspicuously in the eastern samples. Dolomite rhombs are locally important, particularly in the Oued Bou Frah. The proportion of igneous to metamorphic quartz in this region reaches its highest level in the Moroccan samples, and the proportion of quartz to feldspar continues to increase.

PROVINCE T.—This province includes the west side of Al Hoceima Bay and extends to the Oued Nekor. The Rhis and Nekor comprise the two main drainage systems. Amphiboles are the dominant, nonopaque mineral group and include substantial proportions of actinolite, rare elsewhere in the Moroccan assemblages. The amphibole percentages decrease toward the west of Oued Nekor. An increase in the proportion of epidote is accompanied by a decrease in metamorphic minerals. Epidotes decrease eastward from Al Hoceima. Dolomite proportions are universally high and reach a maximum value in sample M33 (Oued Rhis). There is a notable decrease in the quartz to feldspar ratio as compared to Province S and R and a slight decline in the ratio of igneous to metamorphic quartz.

STRAIT OF GIBRALTAR REGION

STRAIT CHANNEL, NORTH PROVINCE.—The material examined lies in the northern of the two deep channels, passing through the Strait of Gibraltar (Kelling and Stanley, 1972a, b). The heavy fraction is distinguished by relatively high values of pyroxenes and garnet and low values of ZTR and amphibole. The mean total quartz and potash feldspar values are the highest noted in the Strait region. There is a considerable excess of igneous over metamorphic quartz, as in all the Strait provinces. Mica content is minimal.

STRAIT CHANNEL, SOUTH PROVINCE.—These samples were obtained in the South Channel sector of the Strait proper. The heavy mineral assemblage is characterized by high values of opaque minerals and the maximum ZTR and clinopyroxenes. Garnet, metamorphic minerals, and ortho-


Cap Spartel
TANGER
Punta Cires
ALCAZAR ZEGOUER
CEUTA
Cap Negro
TETOUAN
O. Martin
O. Laou
BOUHAMED
M'Ter
PLAGIOCLASE
K FELDSPAR
MUSCOVITE & WHITE MICA
BIOTITE
QUARTZ IGNEOUS
METAMORPHIC
CARBONATES
GLAUCONITE
ROCK FRAGMENTS
OPAQUE
OTHERS
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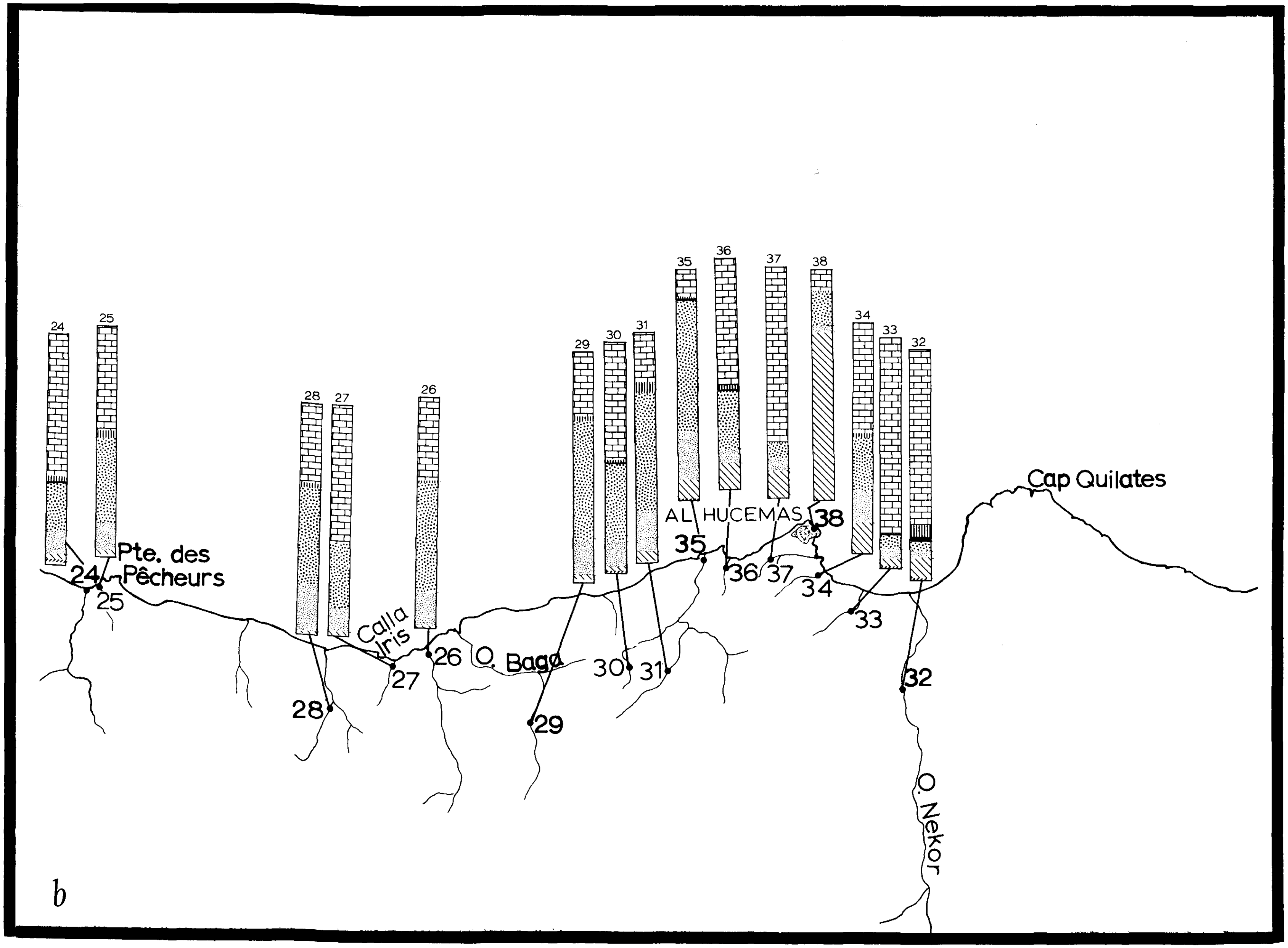

FIGURE 10.—Bar diagrams showing the relative percentages of principal light minerals on the northern Moroccan margin.

pyroxenes are minimal. Garnets and orthopyroxenes increase from west to east, while the clinopyroxenes, epidotes, and amphiboles show a broad reverse trend. The light fraction is distinguished by minimal values of total quartz and feldspar, together with a low proportion of mica and chlorite. Carbonates (mainly shell debris) are the dominant light component.

GIBRALTAR CANYON PROVINCE.—The samples were obtained from the Gibraltar Canyon, both in the axial region and on the adjacent flanks between the northern portion of Algeciras Bay and the zone of confluence at the eastern end of the Strait (see Kelling and Stanley, 1972b, fig. 14). The heavy fraction comprises the highest mean values of metamorphic minerals and amphiboles, together with a considerable amount of orthopyroxenes. Opaque minerals occur in amounts similar to those in the North Channel, while the mean clinopyroxene value is the lowest encountered in the Strait region samples. The proportion of amphiboles broadly decreases down-canyon until the flat east sector of the Strait and then increases slightly. The light fraction is characterized by the highest proportion of igneous to metamorphic quartz, total feldspar and plagioclase, and mica in the Strait region; the lowest values of carbonate (shell debris) are noted here.

CEUTA CANYON PROVINCE.—The samples were collected from the axial region of the Ceuta Canyon to the southern flat region of confluence at the eastern end of the Strait (Kelling and Stanley, 1972b, fig. 14). Heavy minerals in this region are characterized by the highest mean value of garnet, epidote, and olivine in the Strait region. Garnet increases down-canyon, while orthopyroxenes decrease in the same direction. The light fraction is distinguished by the highest quartz to feldspar ratio in the Strait region.

ALBORAN SEA

GIBRALTAR VALLEY–MÁLAGA LOW PROVINCE.—Samples in this province were derived from core

TABLE 8.—*Mineralogic composition of Alboran deep-sea samples–province and core means* (see Figures 5 and 6)

PROVINCE OR CORE	GC	CC	SS	SN	91	92	93	97	98	101	107	108
Opaque Minerals	11.4	20.0	27.8	10.9	17.7	22.5	20.9	27.0	28.0	28.8	15.6	12.9
Zircon + Tourmaline + Rutile (ZTR)	7.0	6.8	7.3	2.0	5.1	5.4	3.7	2.9	1.8	2.2	6.2	5.2
Orthopyroxenes	28.4	17.4	15.9	35.1	35.8[6]	35.1	40.6	41.3	43.3	39.3	38.5	42.0
Clinopyroxenes	3.4	6.5	12.3	8.1								
Amphiboles	6.7	4.7	5.6	2.7	2.5	3.6	2.5	2.2	4.3	2.6	7.5	4.6
Metamorphic Group[1]	18.6	12.9	10.1	14.4	5.1	6.4	4.8	3.6	4.9	3.3	4.2	9.7
Garnets	16.7	22.1	11.6	21.9	9.4	16.3	10.8	4.4	4.9	4.0	11.7	9.3
Olivine + Spinel	3.2	3.9	3.8	2.0	tr.[7]	-	tr.	tr.	-	-	-	-
Epidote Group	2.2	3.6	3.5	1.4	20.8	9.9	15.8	12.9	10.4	15.7	13.8	12.7
Others[2]	2.4	2.1	2.1	1.5	3.2	0.8	-	5.7	2.4	4.1	2.5	3.6
Igneous Quartz[3]	34.0	30.0	21.1	41.3								
Metamorphic Quartz[4]	10.6	12.9	8.3	13.8								
Total Quartz	44.6	42.9	29.4	55.1	17.8	52.2	35.0	24.9	31.3	28.8	44.0	51.3
Igneous/Metamorphic Quartz Ratio	3.21	2.33	2.54	2.99								
Potash Feldspar	0.8	1.6	2.6	3.4								
Plagioclase	7.0	3.6	1.5	3.8								
Total Feldspar	7.8	5.2	4.1	7.2	0.8	2.0	0.5	tr.	1.9	1.4	2.2	2.2
Quartz/Feldspar Ratio	6.56	8.20	7.17	7.65	44.5	26.1	70.0	-	15.6	20.6	20.0	23.3
Micas + Chlorite	5.4	4.5	1.6	1.0	20.5	18.2	14.8	18.4	14.1	11.5	9.7	10.4
Carbonates	25.4	28.2	57.8	29.7	51.4	26.9	51.8	48.9	40.6	54.3	39.1	33.0
Others[5]	16.8	19.2	7.1	7.0	9.5	0.7	-	7.8	12.1	4.0	5.0	3.1
NO. OF SAMPLES	5	3	4	2	2	3	2	2	2	3	5	3

1-4. (as on other tables)
5. Mainly rock-fragments and carbonaceous debris
6. Total pyroxenes, undifferentiated
7. tr. = trace (< 0.5%)

GC = Gibraltar Canyon; CC = Ceuta Canyon;
SS = Strait of Gibraltar, southern sector;
SN = Strait of Gibraltar, northern sector.

108 in the Gibraltar Submarine Valley and core 107 from the Málaga Low, north of the Western Alboran Basin (Figures 1, 5, and 6). One graded sand layer in core 108 and two in core 107 were analyzed (Huang and Stanley, 1972). The heavy mineral assemblage is characterized by substantial amounts of pyroxenes, amphiboles, and ZTR and relatively low values of opaque minerals and garnet. Olivine was not encountered. The light fraction has a very low proportion of feldspar, and quartz accounts for approximately half of the light assemblage. The high carbonate values are largely attributable to concentrations of foraminifera.

WESTERN ALBORAN BASIN PROVINCE.—Samples were collected from the same sand layer (Lower sand-and-silt layer) from six cores in cores 91, 92, 93, 97, 98, and 101 (Huang and Stanley, 1972, figs. 7, 8) in the flat plain of the Western Alboran Basin. An average grouping of all sample data examined shows a heavy mineral assemblage, which is dominated by pyroxenes and epidote with high values of ZTR. Quartz accounts for about one-third of the light fraction, and the carbonates (mainly planktonic foraminifera) constitute about the same proportion. Feldspars are notably deficient. A subtle regional trend can be discovered on both sides of an east-west line bisecting the basin plain. Samples to the south (cores 91, 92, 93) contain somewhat higher values of ZTR, garnet, epidote, total quartz, and mica, whereas those to the north (cores 97, 98, 101) contain slightly enhanced amounts of opaque minerals, pyroxenes, and carbonates.

Provenance of Sediments on Alboran Sea Margins

GENERAL

The regional distribution of mineral groups on the southern Iberian and Moroccan margins is defined in terms of 20 light and heavy mineral provinces as described in the previous sections. The position of these mineral provinces (Figures 5 and 6) is broadly concordant with the seaward limits of the major drainage basins (Figures 2 and 3). This emphasizes the close relationship which exists between the varied lithology of the mountainous margins of the Iberian Peninsula and North Africa and the mineralogical composition of sediments along the adjacent coast. The following section details the manner in which the composition of coastal and fluvial samples can be related to specific source terrains in the Betic Cordillera and the Rif.

Essentially, two major mineralogical sectors are recognized on the Spanish margin: one to the east, extending from Vélez-Málaga toward Adra, influenced by the Nevado-Filábride and Alpujárride complexes, and the other, west of Málaga, draining the ultrabasic rocks of the Peridotite Complex.

In the former region, the Adra and Guadalfeo rivers, as well as smaller intervening rivers, carry, among others, the following minerals: sodic plagioclase (albite, oligoclase), quartz, carbonates, mica, garnet (very abundant), epidote, amphibole, orthopyroxene, and opaque minerals.

In the western region, peridotites are among the significant lithologies that crop out in basins of the Guadalhorce, Fuengirola, and Verde rivers and smaller basins between Málaga and Estepona. These rivers carry the following: calcic plagioclase (or calco-sodic varieties), mica, olivine, amphibole, orthopyroxene, clinopyroxene, garnet, epidote, and opaque minerals.

On the Moroccan margin, two major mineralogical sectors are also recognized: one to the east, extending from the Beni Bouchera ultrabasic complex, influenced essentially by Paleozoic, Mesozoic, and Tertiary sediments, and the other, north and west of the ultrabasic complex, draining Paleozoic sediments, metamorphic rocks, and basic or ultrabasic intrusives.

In the former, rivers such as the Nekor and Ouringa convey sodic plagioclase, both igneous and metamorphic quartz, carbonates, and opaque heavy minerals (very abundant). In the northwestern region, rivers such as the Oued Laou and Martin carry more calcic plagioclase and a high proportion of metamorphic quartz, together with garnet, orthopyroxene, and olivine.

A study of minerals in coastal sediments from the Spanish margin east of Málaga by Pérez-Mateos et al. (1973) provides results which differ in some major respects from those of this investigation. These authors show substantially higher values of minerals such as andalusite, staurolite, and quartz and much lower values of pyroxene, epidote, and feldspar than analyzed here. Furthermore, they recognize three provinces (I, II, III) between Málaga and the Cabo de Gata as compared to five defined by us along the same sector

(Provinces I to M). A point of resemblance, however, is that the dramatic increase in the proportion of garnet to the east of Motríl (Río Guadalfeo) (Figure 7) is also recorded by Pérez-Mateos and others (1973).

Origin of Selected Spanish River Sediments

Two samples from each of six rivers in the western sector of the Iberian margin (west of Marbella) were examined: Calena (I), Guadaiza (II), Guadalmansa (III), Padrón (IV), Enmedia (V), and the Genal-Guadiaro (VI). These rivers fall within the coastal mineral provinces G, F, and E, from east to west respectively.

At each of the river localities the sample pairs show similar heavy mineral associations, and consequently an average value is supplied for each river (Table 5). Each river sample closely reflects the lithology of the terrain traversed. Thus, the main variations from river to river are most readily ascribed to differences in lithology of the terrains cut by the six rivers (cf., Figure 2). The notable increase in quartz and mica and orthopyroxene, amphibole, olivine, and metamorphic minerals and the concurrent decrease of carbonate, garnet and opaque minerals, from the Calena to the neighboring Guadaiza river, are explained by the fact that the first river cuts carbonate-rich rocks, while the second (Guadaiza) cuts across peridotites as well as metamorphic terrains. The westernmost river, the Genal-Guadiaro, carries an assemblage that is more similar to that of the Guadaiza River than the intervening rivers. The headwaters of the Genal-Guadiaro also erode peridotites and metamorphic lithologies.

The percentage of total quartz increases substantially to the west, reflecting the westward predominance of source terrains of Cretaceous, Paleogene, and Miocene sediments.

Samples collected from these rivers are broadly comparable in composition to the samples collected on the coast adjacent to the appropriate river mouth. However, with the exception of epidote, which appears to be consistently more common in the coastal samples, there is little change downstream. As a general rule, coastal samples contain higher values of opaque minerals and lower values of orthopyroxenes. Moreover, the river samples in aggregate generally contain more quartz and mica and less feldspar than most of the coastal sands (Table 5, Figure 6).

These differences in composition between fluvial and coastal samples may be partly a function of the relative efficacy of the differing hydraulic processes affecting these two environments, but the influence of grain-size factor cannot be excluded (despite the restrictions of analyses to the same grades, as indicated earlier, page 3).

Origin of Spanish Margin Sediments—Light Minerals

Quartz is marginally the most abundant mineral, ranging from 29% to 71% of the total light mineral fraction (the average content approximates 40%). Metamorphic quartz is more abundant than quartz of igneous origin. The former originates in metamorphic terrains that abound in the study area. Quartz of igneous origin is derived from several sources: the acid volcanics of the Cabo de Gata region, hydrothermal veins in the different complexes, and reworked older sands and sandstones, particularly those in the External Zone. Plagioclase generally constitutes between 10% and 56% of the light mineral fraction, averaging about 35%. Both sodic and calcic plagioclases display distinct regional distributions. Sodic plagioclase (albite and oligoclase) is predominant east of Málaga; calcic species abound between Estepona and Málaga. As would be expected, the relation between plagioclase assemblages and river supply is a direct one. For instance, sodic plagioclases are common in the rocks of the Nevado-Filábride and Alpujárride complexes, i.e., sequences that crop out in the fluvial basins east of Málaga. An important source of calcic feldspars, on the other hand, is the Peridotite Complex that crops out in basins between Málaga and Estepona. Between Estepona and Tarifa, farther to the west, both sodic and calcic varieties occur.

The lower relative percentages of potassic feldspars (generally less than 2%) in all coastal samples examined can be related to their generally low abundance in most rock types of the different stratigraphic-tectonic units cropping out in the various drainage basins. An exception is Province C, on the eastern side of Algeciras Bay, where the increased quantity (to 8%) may reflect the importance of sedimentary sources conveyed into the northern part of the Bay from the Río Guadarranque.

Carbonate, including dolomite rhombs, and lithic fragments are commonly present and in many cases can be related to specific carbonate rock types cropping out in the drainage basins. The highest percentages occur in Province L, which is bounded by cliffs of Middle to Upper Triassic shaly limestones and dolomites. High values are also encountered in Provinces G and H and appear to represent fluvial supply from the Sierra Blanca unit, which includes marbles and gneisses.

Glauconite, essentially of detrital origin, is observed in some samples. Most of the detrital glauconite originates in the sandstones of Cretaceous, Paleogene, and lower Miocene age in the External Zone and in sands and sandstones of postorogenic sequences (especially the Miocene).

The percentage of mica is variable, but is generally quite low (less than 2%). Muscovite and particularly biotite abound in most of the metamorphic sequences of the Internal Zone. The highest mica values (12%) occur in Province K east of Nerja, west of Motríl, where Paleozoic micaschists and quartzites crop out in the coastal ranges. Certain other coastal samples contain a notably high percentage of mica. An example in point are those in the Bay of Algeciras which, interestingly enough, are fed by rivers that cut metamorphic units not particularly rich in mica. This suggests that enriched mica content may also be related to factors other than provenance (see following section).

Origin of Spanish Margin Sediments—Heavy Minerals

Garnets occur at all sample stations along the Spanish margin (Figure 7), and a large fraction of these undoubtedly are derived from the Nevado-Filábride Complex. In addition, garnets are supplied from certain Alpujárride Complex sequences, from basal units of the Maláguide Complex, and from the Casares Unit. The highest percentages of garnet occur in samples from the sector between the mouths of the Adra and Gualdalfeo rivers. These rivers traverse extensive outcrops of the Nevado-Filábride Complex (Figure 2). Other areas where high amounts of garnet occur include coastal sections near the mouths of the Guadalhorce and Fuengirola rivers, where garnetiferous sequences of the Maláguide Complex crop out.

High values of epidote occur along the coast, and the highest concentrations are found in the region between Málaga and Motríl, and in some sectors to the west of Adra. This mineral has different possible origins that include the Nevado-Filábride and Alpujárride Complexes as well as certain sequences of the Maláguide Complex.

Pyroxenes are abundant west of Motríl. Percentages of orthopyroxenes are higher than those of clinopyroxenes except in certain isolated cases (sample stations 2, 20, 35 and 74). Provenance of pyroxenes (ortho- as well as clinopyroxenes) is closely related to the Peridotite Complex. Some clinopyroxenes are derived from the amphibolites of the Alpujárride Complex that are intercalated in the Paleozoic dolomites exposed west of Motríl.

Amphiboles are present in all samples in variable amounts. In some sectors, such as near Nerja, it is the most important mineral in the heavy fraction in some samples. Here, its origin lies in the amphibolites of the Paleozoic sequences of the Alpujárride Complex that crop out extensively north of the coast between Nerja and Motríl.

Olivine is derived in large part from the Peridotite Complex, and the highest percentages observed in coastal samples occur between Estepona and Marbella, where rivers eroding this complex reach the sea. Olivine is abundant from Algeciras to Málaga; this in part explained by the load carried by the various rivers (Guadalhorce, Fuengirola, Verde) cutting this complex and is also due to coastal currents carrying olivine-bearing sediments toward the west (see next chapter). At the mouth of the Guadalfeo River there is an anomalously high percentage of olivine; this can be interpreted as originating in the "rocas verdes" (altered basic igneous rocks) facies of the Nevado-Filábride and Alpujárride complex that crop out in the drainage basin of this river.

Significant percentages of apatite occur only in samples collected in the vicinity of the Strait of Gibraltar. Apatite, derived in large part from igneous rocks, is transported by currents from source terrains that are exposed along this coastal sector. There is no primary source for this mineral in the fluvial basins north of this area. The presence of very rounded grains does suggest that apatite is reworked, at least in part, from older apatite-bearing sandstones.

Tourmaline is derived from the Nevado-Filábride Complex, phyllites of the Alpujárride Complex and the Casares Unit, and the amphibolites of diverse units. The total ZTR content ranges up to 2.3% and is more abundant in the coastal samples from the Strait of Gibraltar region, tending to decrease eastward from this area. This change results from the diminished importance of sedimentary terrains east of Gibraltar.

Kyanite is associated with certain lithologic sections (micaschists) of the Nevado-Filábride Complex. Sillimanite originates in rocks, including micaschists, of possible pre-Cambrian age in the Maláguide Complex and the Sierra Blanca Unit. Andalusite is derived from several units: micaschist of the Alpujárride Complex, lower sequences of the Paleozoic Maláguide Unit, the Casares Unit, and the Sierra Blanca Unit. The percentages are noteworthy along the coast from Nerja toward the west.

Opaque minerals are present, generally in high percentages. Particularly significant are coastal samples containing large amounts of opaques (45% to 60%) between Málaga and the Motríl-Adra sector and the Strait of Gibraltar sector. Of these minerals, magnetite is very abundant in the fine sands of this coast (beaches such as the Playa de Carchuna near Motríl). Magnetite has several possible origins and can be found in diverse stratigraphic sections of sedimentary and metamorphic as well as ultrabasic rocks.

Origin of Moroccan Margin Sediments—Light Minerals

Feldspar, particularly plagioclase, is the most abundant mineral, ranging from 25% to 75% of the total light mineral fraction (the average content approximates 43%). Plagioclase generally constitutes between 27 and 71%, and calcic varieties predominate, particularly in the central sectors (Provinces O, P, Q, and R). High values of calcic plagioclase in the sediments of Provinces P and Q reflect a source terrain which includes bodies of ultrabasic rock (Beni Bouchera). Individual coastal samples from the vicinity of Cabo Negro in Province O also contain enhanced proportions of calcic plagioclase, probably derived from the peridotite bodies intruded into the Paleozoic metamorphic rocks of this region (Figure 3). High values of more sodic plagioclase are encountered in the sediments of Province T and probably derive, directly or indirectly, from isolated outcrops of Paleozoic metamorphic rocks in the drainage basin of the Oued Nekor.

Total quartz, ranging from 17% to 66%, is most abundant in the western sectors (Provinces N and O) and also in Province S, west of Al Hoceima (to 52%). These areas drain essentially sedimentary terrains. The igneous quartz variety predominates over the metamorphic type in those provinces cited above which contain abundant total quartz of presumably sedimentary origin, whereas the metamorphic quartz is dominant in Provinces such as P, Q, and R, receiving material largely from Paleozoic metamorphic sources. The dominance of igneous quartz in Province T probably reflects the derivation of material from acid and intermediate volcanic rocks of late Mesozoic and Tertiary age including the Cap Quilates Complex.

Carbonate content generally ranges between 4% and 8%, but reaches the exceptionally high mean value of 22% in Province T east of Al Hoceima. Dolomite rhombs constitute an important part of the carbonate fraction and reach their peak abundance in samples from the Oued Nekor drainage basin. Such carbonate components derive largely from Mesozoic limestone and dolomite sequences, particularly those of Triassic and early Jurassic age, most commonly exposed in the eastern part of the study area. High values of carbonate in individual samples (Figure 6) which occur in Provinces N, O, and P may be ascribed to a similar provenance, although some may also be derived from smaller bodies of marble developed in the Paleozoic terrains between Ceuta and Bouhamed.

Glauconite is generally rare in the Moroccan samples except in a sample (no. 3) east of Tangier in the Strait of Gibraltar (Figure 10), whose origin lies in the adjacent terrain of Cretaceous/Tertiary sandstones.

Rock fragments account for only a minor proportion of the light fraction except in sample 6 just west of Cueta, where they consist mainly of slate.

Mica percentages are generally low and consist predominantly of biotite. The highest values, encountered in Province P, are attributable to the adjacent Paleozoic sediments.

Origin of Moroccan Margin Sediments—Heavy Minerals

In general, garnets account for the highest percentage of transparent heavy mineral fraction but vary considerably in abundance (1.1% to 18.4%). The highest values occur in river sediment samples from the Province Q (Bouhamed) region and in coastal samples from the Strait of Gibraltar and the region south of Ceuta (Provinces N and O). Paleozoic metamorphic rocks represent the primary source of this mineral and account for its abundance in the Bouhamed region. However, the abundance of garnet in the coastal sediments may be attributed either to reworking of younger sedimentary rocks or to preferential concentration by littoral processes.

The ZTR group is generally an important constituent of most of the Moroccan heavy fraction (4% to 18% mean values), and varieties of zircon tend to dominate the group. Exceptionally high values of ZTR occur in samples from Province S (west of Al Hoceima) and from the Strait of Gibraltar region. These enhanced proportions clearly indicate the increased importance of sedimentary rocks in the source terrains.

Minerals assigned to the metamorphic group (andalusite, kyanite, staurolite, and sillimanite) are also abundant in the heavy mineral assemblages from the Moroccan margin, ranging from 4% to 15% mean values. This group attains its maximum abundance in the region south of Ceuta (Province O), although high mean values also occur in the Bouhamed area (Province Q) adjacent to extensive outcrops of metamorphosed Paleozoic rocks. High values in the Strait of Gibraltar (Province N) are mainly observed in the littoral samples and probably reflect the increased resistance of certain members of this group, notably staurolite. Staurolite constitutes 12.2% of the nonopaque fraction in individual samples but is almost confined to Provinces N and O in the western portion of the study area. This mineral recurs in lesser abundance in the samples from the Bouhamed metamorphic area (Province Q, Figure 5). Andalusite is common, but exceptionally large values are noted in individual samples from Provinces R, S, and T near Al Hoceima. They are evidently reworked from Mesozoic and Tertiary sediments, an origin confirmed by the well-rounded character of these grains. Large relative values of kyanite are also noted in the same samples. However, angular grains of kyanite are consistently abundant in samples from Provinces O and Q (south of Ceuta and Bouhamed) where such grains may be more confidently attributed to the surrounding metamorphic rocks.

Orthopyroxenes are highly variable in abundance (up to 24% in individual samples) and are almost confined to Provinces O and Q. The enhanced content of the orthopyroxene in these regions reflects the presence of ultrabasic bodies occurring in the vicinity. Clinopyroxene is more widespread than the orthopyroxene but is almost always lower in value. The highest percentages of clinopyroxene are found in Provinces O and Q. Somewhat enhanced proportions of clinopyroxene occur in coastal samples from the Pointe de Pêcheurs area (Province R) and here may be derived from the basic or ultrabasic intrusives nearby. A sample from the Oued Nekor provides the highest individual value of clinopyroxene, which probably originates from igneous or metamorphic rocks that crop out in small areas near the source of this river.

Province T, in the Oued Nekor drainage basin, also provides the consistently highest content of amphibole minerals, including substantial amounts of actinolite, which is typical of the amphibolite metamorphic facies. The minor amounts of amphibole encountered in the more westerly regions (especially Province Q) are dominated by brown and green hornblende, together with some glaucophane. These minerals probably originated in the Paleozoic metasediments.

Olivine and spinel (mainly picotite) are considered together because these minerals are derived largely from basic and ultrabasic rocks in which these two species are intimately associated. The distribution of olivine and spinel closely parallels the distribution of orthopyroxene, confirming the basic or ultrabasic provenance of these minerals. The maximum values for this group occur in the region between Pointe Targa and Bouhamed, reflecting the influence of the Beni Bouchera igneous mass.

Epidote attains maximum abundance in Provinces Q and T, areas rich in metamorphic source terrains.

Apatite is relatively uncommon on the Moroccan margin but attains appreciable abundance (up to 4.7%) in individual samples from the Strait of Gibraltar beaches. Grains are well rounded and, in part, may be reworked from older sedimentary terrains.

Opaque minerals comprise the most important component of the heavy mineral fraction, with mean values ranging from 23% to 80% and averaging approximately 45%. The highest mean values occur in rivers and beaches in the more easterly provinces (R, S and T), together with Province P (Cap Mazari area). Opaques are probably derived from sedimentary and metasedimentary rocks, although this provenance is diverse and subsequent concentration by both fluvial and coastal processes has also occurred.

Mineralogical Modification by Coastal Processes

Although the similarity of heavy and light mineral assemblages in river and adjacent coastal samples attests to the virtually direct transport of sediment from source to sea on all margins of the Alboran Sea, several features indicate that some modification of mineralogy does occur while material is held in the littoral and nearshore zone. The nature of these modifications may be used to interpret the effects of coastal processes and the consequent dispersal pattern on both Iberian and Moroccan margins.

The most compelling evidence for modification by coastal processes derives from the nonconcordance in detail of mineral province boundaries

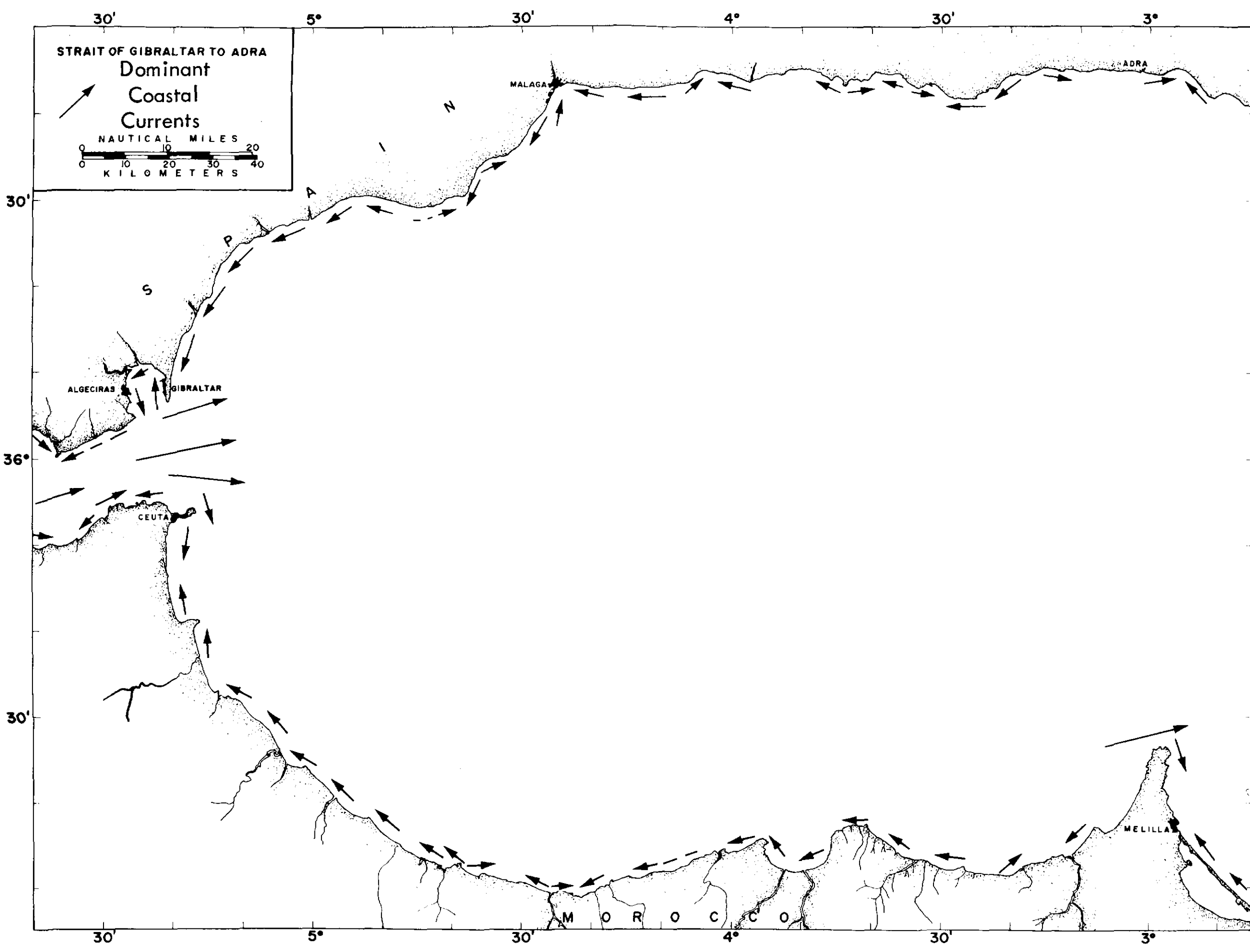

FIGURE 11.—Predominant movement of coastal and nearshore currents based primarily on aerial photographic analysis (cf. Figures 12–14).

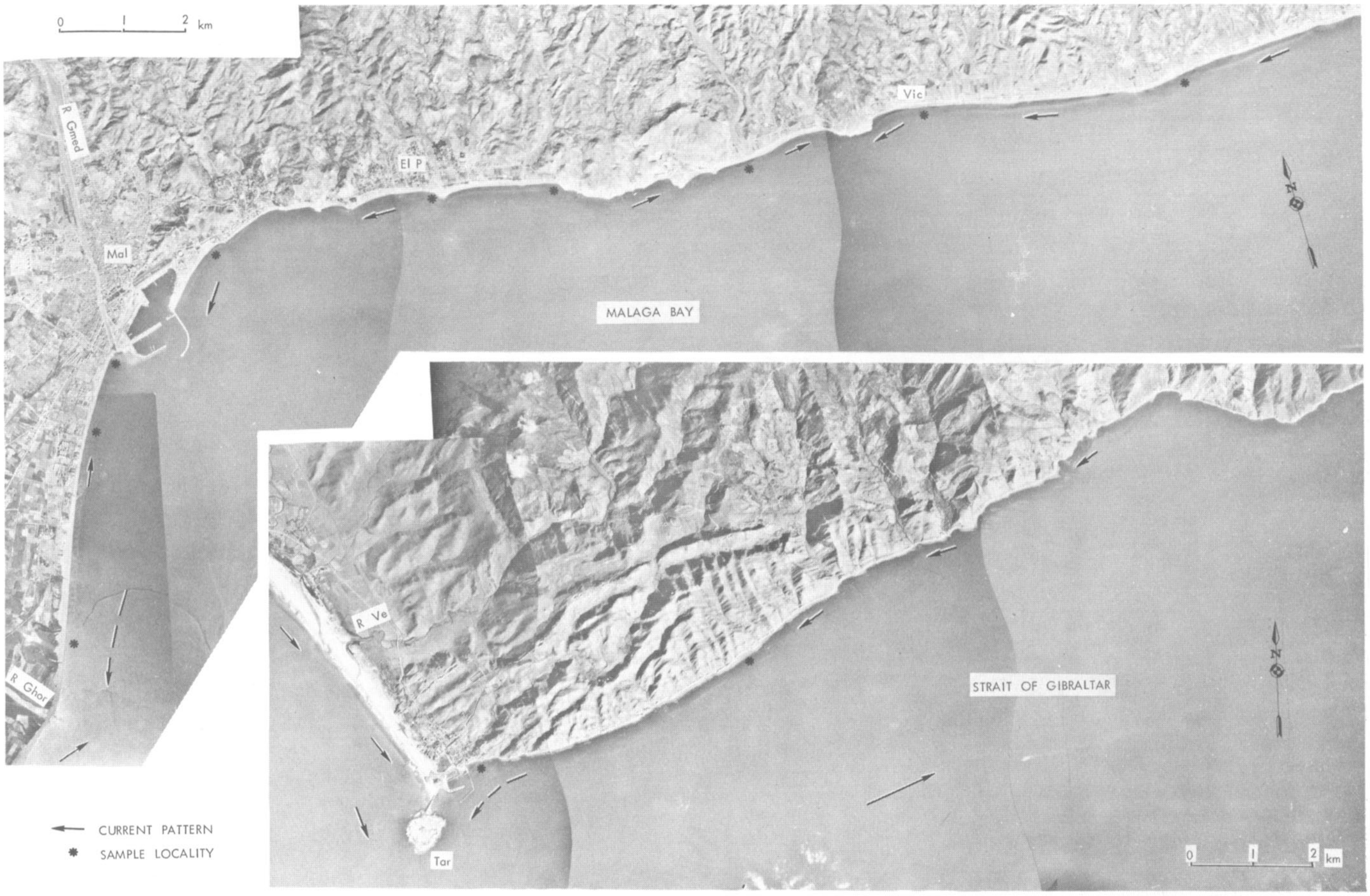

FIGURE 12.—Aerial photographic coverage of selected portions of the southern Iberian margin (arrows denote major current pattern). *Upper:* Málaga Bay (altitude approximately 7000 m; R. Ghor = Río Guadalhorce; R. Gmed = Río Guadalmedina; Mal = Málaga; El P = El Palo; Vic = La Victoria). *Lower:* Strait of Gibraltar (altitude approximately 7000 m; R. Ve = Río de la Vega; Tar = Tarifa).

with the adjacent drainage basin boundaries, despite the broad parallelism already noted. Important and abrupt variations in the mineralogy of the coastal sands are related to the supply at a river mouth or to the presence of coastal outcrops directly supplying material to the adjacent beach. However, where examined in detail (see previous section), the mineralogical variation from river to river is greater than that observed along the intervening stretch of coast near the river mouths.

An example of this effect is shown by the comparison of coastal and fluvial materials on the Spanish margin between the Calena and Genal-Guadiaro rivers. Here, coastal stations 27 to 30 (Figure 2) display a greater increase in the percentage of garnet than is observed between the supplying rivers (Enmedia and Padrón). Stations 22 to 29 contain appreciably enhanced proportions of olivine as compared to adjacent rivers, and both clinopyroxene and amphibole are less abundant in samples from the corresponding rivers than in the sands from coastal stations 27 to 36. There is, in addition, a much higher content of orthopyroxene observed in all the coastal samples as compared with the fluvial sediments. Thus, river samples, as would be expected, reflect more directly the mineralogy of the terrains crossed by the fluvial flow, while the greater sample-to-sample similarity along the coast indicates that at least some mixing and dilution of individual river supply

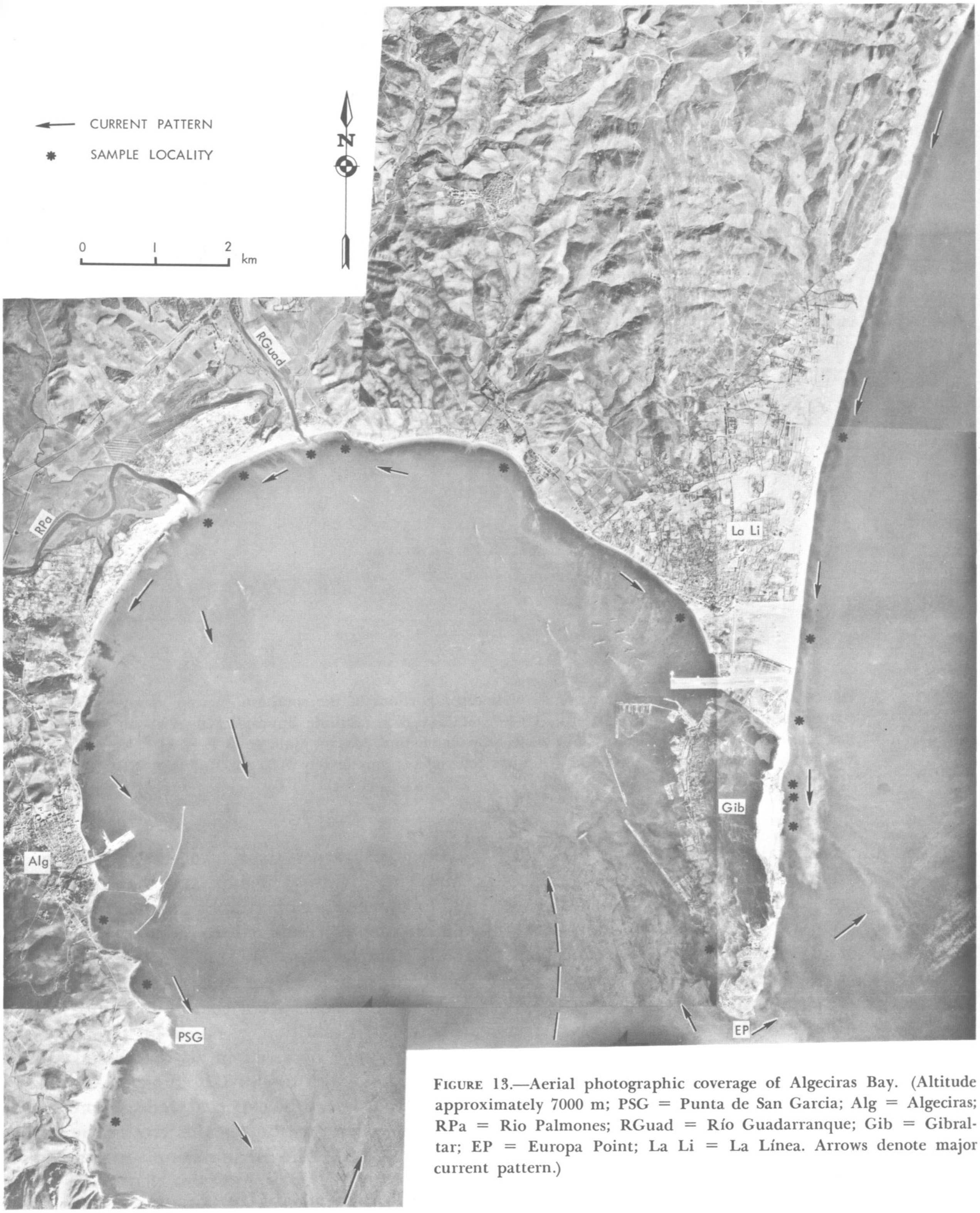

FIGURE 13.—Aerial photographic coverage of Algeciras Bay. (Altitude approximately 7000 m; PSG = Punta de San Garcia; Alg = Algeciras; RPa = Rio Palmones; RGuad = Río Guadarranque; Gib = Gibraltar; EP = Europa Point; La Li = La Línea. Arrows denote major current pattern.)

FIGURE 14.—Aerial photographic coverage of selected portions of the Spanish margin east of Málaga (altitude approximately 5000 m; arrows denote major current pattern). *Upper:* area near Castell de Ferro (= Ca Fe; RaGua = Río Gualchos). *Lower:* area near Calahonda (= Cal; Fa = Faro, light house; B.R. = beach ridges).

has occurred at the coast as a result of wave and longshore current transport.

This example demonstrates that the coastal modification processes are not solely concerned with enhancement of the more stable or resistant mineral species. For example, the increased proportions of pyroxenes in the coastal sands west of Marbella (Figure 7) indicate some increment in these relatively unstable minerals from sources other than the adjacent rivers, presumably through littoral drift from more distant fluvial or coastal sources.

Evidence concerning the actual sense of nearshore sediment transport is provided by the lateral trends observed within both Moroccan and Spanish coastal mineral provinces. Such trends involve distinct, regular diminution or augmentation of the relative proportions of certain mineral species, which may be assigned to supply from a given river or coastal outcrop. For example, in the region of Málaga, samples 48 to 52 show a steady southward decrease in the abundance of amphibole and a concurrent increase in the proportion of garnet and olivine (Figure 7). The implication of this trend is that this stretch of coast is subject to an essentially southwestward longshore movement of sediment by coastal currents. This conclusion is substantiated by an independent appraisal of coastal current motion and long-term sediment drift patterns observed from aerial photographs and large-scale charts (Figures 11 and 12).

The coastal current map suggests a predominance of westerly trending transport along the Spanish coast from Málaga to the Strait of Gibraltar. Surface drift surveys (Gaibar-Puertas, 1967) also reveal a similar pattern. Such transport would help account for the observation that the highest percentage of the main mineral species generally occurs in samples taken immediately west of the river delivering it to the sea (note changes on heavy mineral bar graphs, Figure 7). This southwestward transport is further attested by the remarkably high concentrations of orthopyroxene, amphibole, and olivine in the region of the Strait of Gibraltar, a region isolated from direct fluvial or coastal supply of these minerals.

The distribution of minerals in the coastal sand of the Bay of Algeciras poses some problems in that the mineral assemblages are rich in metamorphic species, pyroxenes and olivine, although the rivers that flow into the Bay do not cross metamorphic or ultrabasic terrains. It is significant, therefore, that the Bay assemblage is similar to assemblages outside of the Bay and east of Gibraltar (Kelling and Stanley, 1972a). There are several possible interpretations: (a) currents from the east, moving around the peninsula of Gibraltar, enter the Bay carrying with them sediments from La Línea and farther east; (b) the sands are eroded from Tertiary-Quaternary sediments that bear this particular suite of minerals and that are exposed near the Bay; (c) or the present peninsula forming the "rock" of Gibraltar was an island

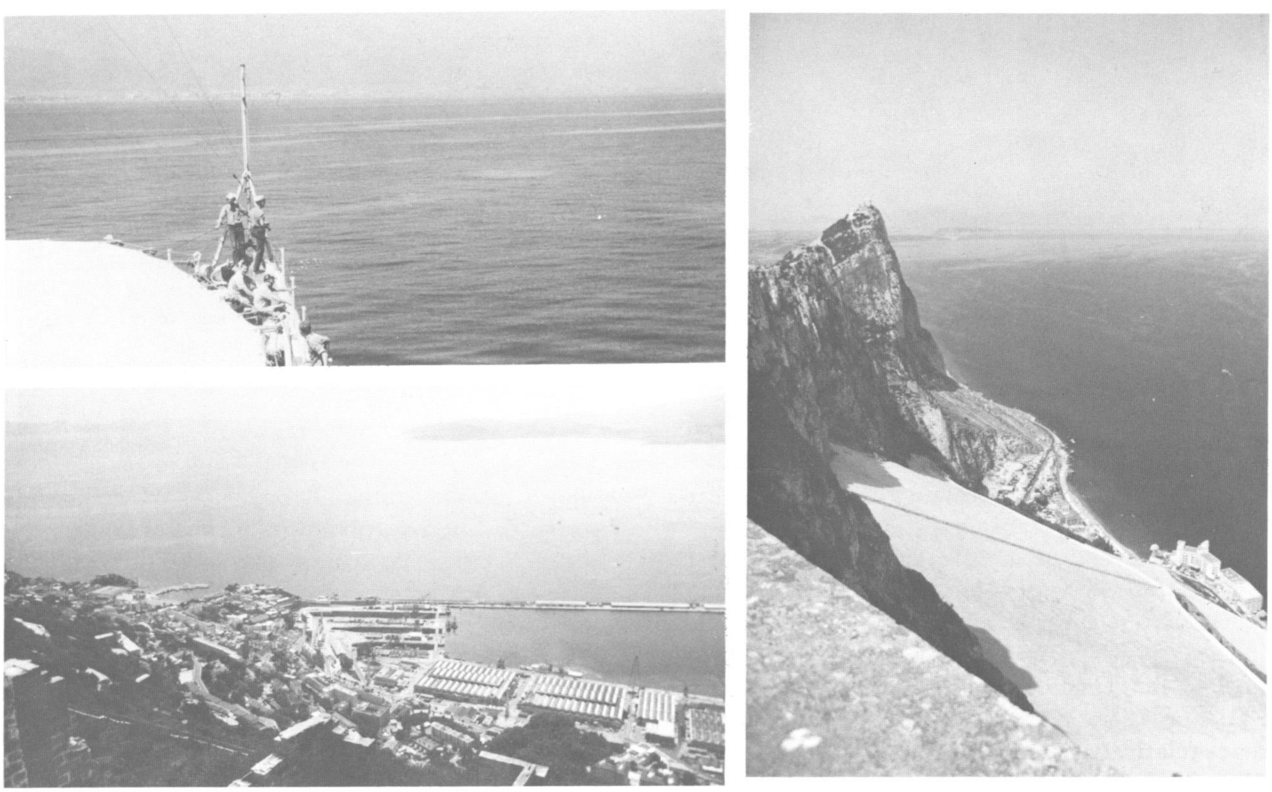

FIGURE 15.—Photographs showing strong coastal currents in the Strait of Gibraltar region. *Upper left:* ship heading west across Algeciras Bay toward Algeciras. *Lower left:* view from the Rock of Gibraltar across Algeciras Bay toward the Strait (to the southwest). *Right:* view showing east side of the Rock and coastline north of Gibraltar. (Note current patterns parallel to the straight coastline off La Línea-Gibraltar region. Large structure in foreground is a water catchment above Catalan Bay.)

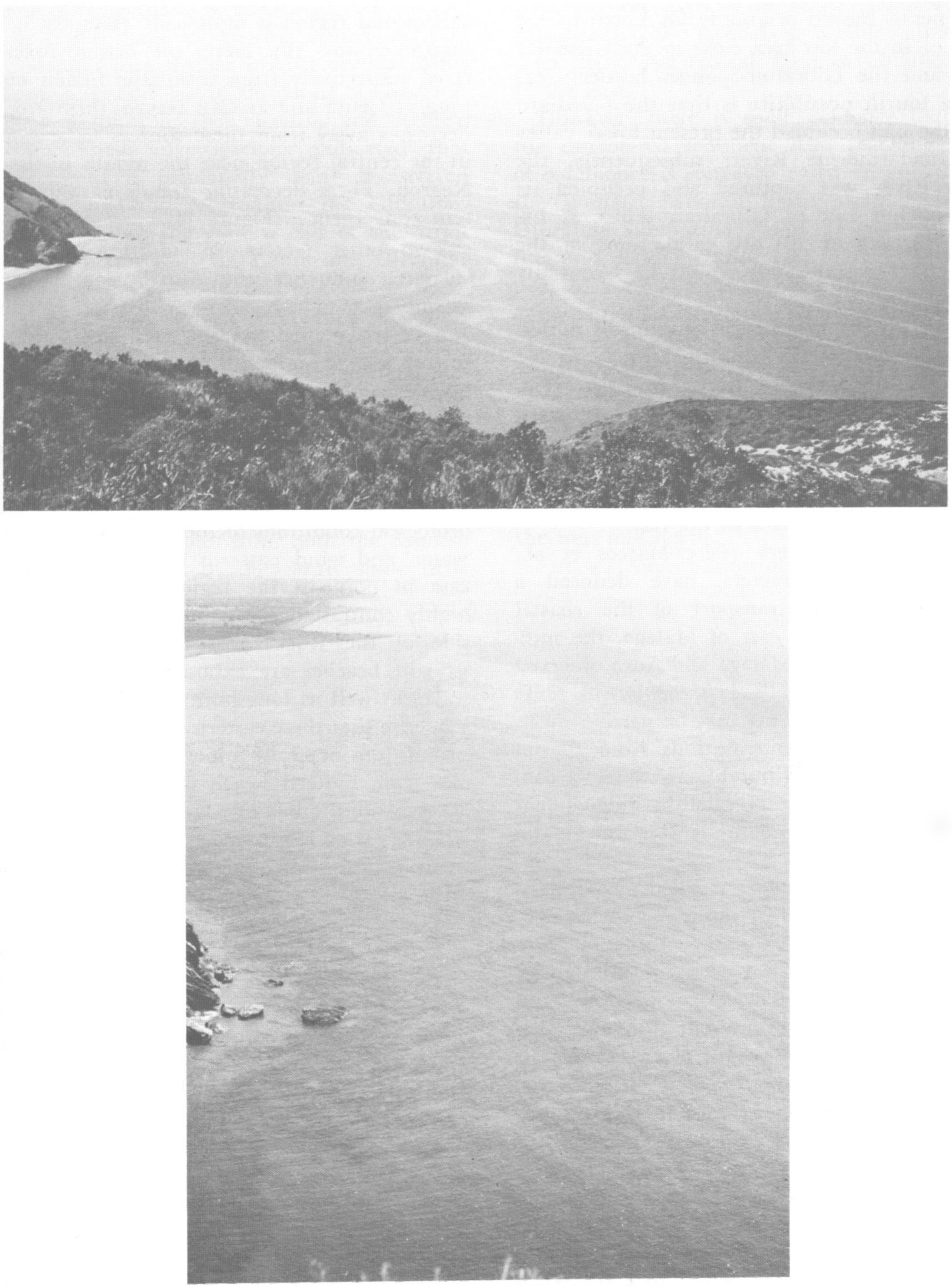

FIGURE 16.—Photographs showing evidence of strong coastal currents. *Upper:* currents off Morocco between Cap Mazari and Cabo Negro. *Lower:* view east toward the plain of Carchuna from Cape Sacratif (southeast of Motríl, Spain).

during the recent past, and the coast line along which minerals moved originally lay north of the "rock" (i.e., in the low area close to the Gibraltar air strip and the Gibraltar-Spanish border); (d) or, still, a fourth possibility is that the Guadiaro River in the past occupied the present lower valley of the Guadarranque River; subsequently, the Guadiaro River was captured and occupied its present position east of Gibraltar. Thus, if hypotheses (b), (c), or (d) are valid, some of the Algeciras Bay coastal sands would be essentially relict in origin.

In any event, the present distribution of minerals in the Bay sediments conforms closely to the predicted counterclockwise transport path (Figures 13 and 15). Note for example the southward diminution of pyroxene in the western part of the Bay (samples 13 to 8) and the northward decrease in orthopyroxene from Europa Point toward La Línea on the eastern side of the Bay.

Although some workers (Pérez-Mateos et al., 1973), using size parameters, have deduced a predominant eastward transport of the coastal sediments in the region east of Málaga, the mineralogic trends between Málaga and Adra observed in this study are generally less regular in sense or in degree. This variability may be partly a function of the increased contributions from coastal outcrops and partly attributable to the less constant coastal drift patterns revealed by independent analysis of the aerial photographs (Figures 11 and 14).

Similar effects of nearshore transport have been identified on the Moroccan margin. Coastal samples from the western part of the Moroccan shore of the Strait of Gibraltar contain substantial quantities of minerals, such as orthopyroxene and olivine, which are virtually absent from the adjacent river sediments. The source of these minerals lies in ultrabasic intrusives exposed on the coast around Ceuta, and their presence in this western region implies a net westward transport of detritus along this portion of the Strait (Figure 11).

As in the region west of Málaga, the predominant nearshore sediment drift, as revealed by aerial photo survey, is essentially toward west and north, in the region from Melilla to Cap Negro (Figures 11 and 16). The region between Cap Negro and Ceuta appears to be one of converging flow (to the south from Ceuta, and to the north from Cap Negro). The mineral distribution in this coastal region is significant (samples 7, 19–22, Figures 9 and 10). Here, the orthopyroxene derived respectively from ultrabasic bodies outcropping at Ceuta and at Cap Negro (Milliard, 1959) decreases away from these sources to a minimum in the central region near the mouth of the Oued Negron. These decreasing trends parallel the current convergence (Figure 11).

Two other factors, in addition to nearshore currents, influence the distribution of mineral assemblages. These are (a) coastal morphology (i.e., embayments and sheltered areas that serve to trap selected minerals such as micas versus long, open straight coastlines that are prone to more intense wave attack with resulting concentration of heavy mineral lag deposits; the orientation of beaches that may be more or less prone to erosion by wave and coastal currents, etc.) and (b) meteorological conditions including rainfall, snow-melt, water, and wind patterns that vary seasonally. A case in point is the region of Gibraltar where highly contrasted coastal regimes occur on either side of the Rock. East of Gibraltar, the long straight beaches are exposed to strong attack by waves as well as longshore currents, with the consequence that these eastern sands contain very high proportions of heavy minerals (up to 71% in samples from Eastern Beach near La Línea). On the other hand, the Bay of Algeciras, west of Gibraltar, is a region of lower energy where deposition prevails, resulting in the enhanced proportions of mica.

It is apparent, therefore, that the abundance of individual mineral species is not solely dependent on provenance but is subject to modification by processes active in the coastal zone. Such processes operate chiefly to concentrate or dissipate specific minerals of differing size, density, or physical durability.

Dispersal of Marginal Sands to the Western Alboran Basin

The evidence cited in the previous section demonstrates that sediment transported by rivers from both the Iberian and Moroccan highlands maintain, at least in a general manner, their mineralogical integrity along well-defined coastal sectors. This fact should enable the provenance of sands in more offshore environments to be identified.

Earlier studies have shown that sand is actively being conveyed into deeper marine environments both to the west and east of the Strait of Gibraltar (Heezen and Johnson, 1969; Kelling and Stanley, 1972a, b). These investigations indicated that coarse sediment is principally being transferred from the Ceuta-Cabo Negro and the Gibraltar-Algeciras regions to the eastern end of the Strait through two major canyons, Ceuta and Gibraltar canyons. From the canyons, this material is transported to a zone of canyon confluence in a relatively flat sector at the eastern end of the Strait (Figure 17) and subsequently is shifted predominantly in a westward direction under the influence of the strong deep Mediterranean undercurrent (Kelling and Stanley, 1972b, figs. 15, 16).

The results of the present study provide independent evidence for this westward transport, since coastal and fluvial samples from both the Spanish and Moroccan borders of the Strait show little mineralogical resemblance to samples from the adjacent deep floor of the Strait (Figures 5 and 6). Significantly, the latter bear a closer mineralogical resemblance to coastal samples obtained farther to the east.

However, there is some evidence that part of the canyon-fed sediment load reaching the zone of confluence is conveyed eastward and may reach the Western Alboran Basin plain via the large Gibraltar Submarine Valley (Figure 18; cf., Kelling and Stanley, 1972b:518). This eastward transport of sand is substantiated by the results of a detailed high-resolution subbottom survey (Stanley et al., 1970; Bartolini et al., 1972) showing the distribution of sand layers in the Western Alboran Basin. The number and thickness of these sand layers provide a means of determining the gross dispersal pattern of late Pleistocene-Holocene clastics within the Basin. These earlier surveys showed that sands were primarily transported from the west and north.

Further confirmation of this mode of filling has

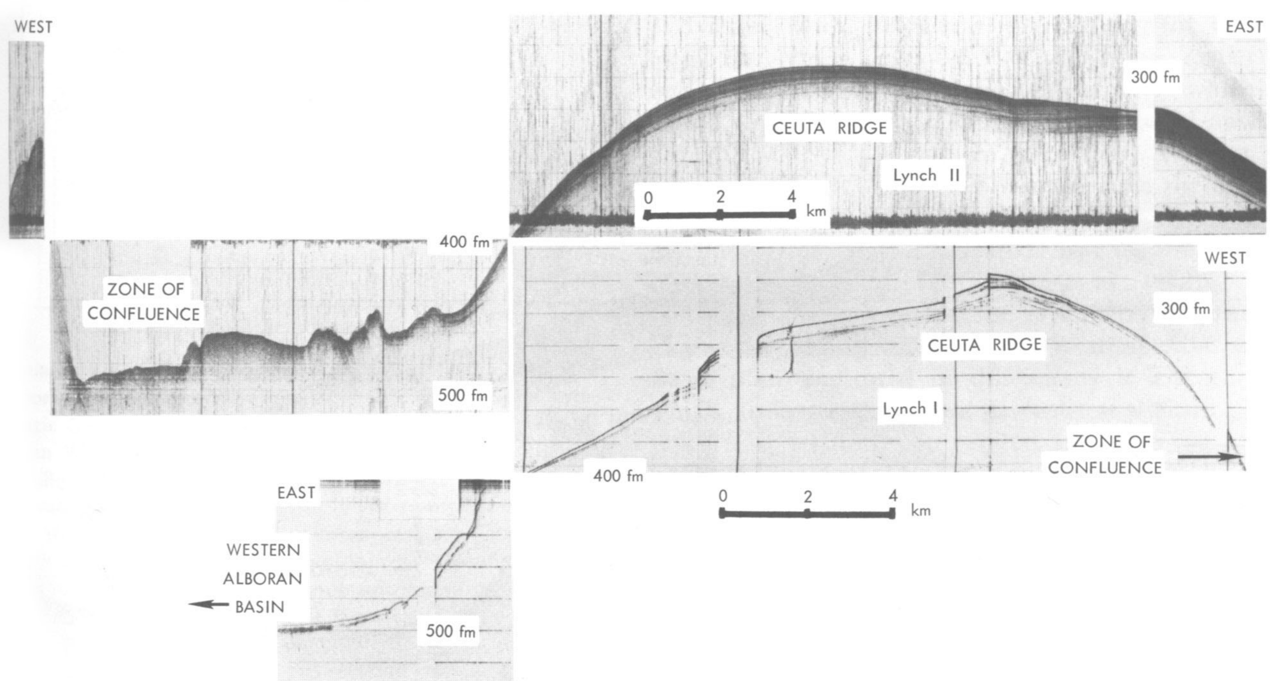

FIGURE 17.—Two east-west high resolution subbottom profiles (3.5 kHz) at the eastern end of the Strait of Gilbraltar showing the zone of confluence, a flat area between Gibraltar and Ceuta. Profiles cross Ceuta Ridge bounding the eastern margin of Ceuta Canyon (see Figure 1). (Spacing between horizontal lines is 20 fm (37 m).)

been provided by compositional studies of the sand layers in numerous cores from the western Alboran Basin plain and surrounding area (Bartolini et al., 1972; Huang and Stanley, 1972). Material from several turbidites was attributed to a source area in the region of the Serranía de Ronda west of Málaga and at the eastern end of the Strait of Gibraltar.

A closer evaluation enables us to identify more precisely the immediate and ultimate sources of the late Quaternary and Holocene sands in the deep-sea cores. It is evident that the heavy mineral assemblages are more valuable for this purpose than the light fraction, partly because of the addition of biogenic carbonate (largely planktonic foraminifera and some shell debris) and mica, and partly because of size-sorting effects. The data of Huang and Stanley (1972, table 5) pertaining to the *Upper sand turbidite layer* (dated at about 10,000 years B.P.) and to the *Lower sand turbidite layer* (emplaced subsequently to about 12,500 years B.P.) in six cores (91, 92, 93, 97, 98, and 101) was re-expressed in order to achieve mineral proportions compatible with those of the shallower regions.

The Western Alboran Basin heavy mineral suite is consistent from core to core and is dominated by pyroxenes and opaque minerals, with substantial proportions of epidote, garnet, and ZTR. On the basis of the mean values of the heavy minerals, the deep-sea sands most closely resemble those of coastal sands in the vicinity of Gibraltar (Provinces B, C, and D). The high proportion of pyroxene precludes derivation of the Alboran Basin sands from coastal areas east of Marbella on the Spanish margin. No assemblage resembling these deep-sea sands occurs on the Moroccan margin (low pyroxene and low epidote).

The ultimate derivation of the Lower sand layer may lie in the Serranía de Ronda as suggested by Bartolini et al. (1972) on the basis of abundant enstatite and also indicated by river

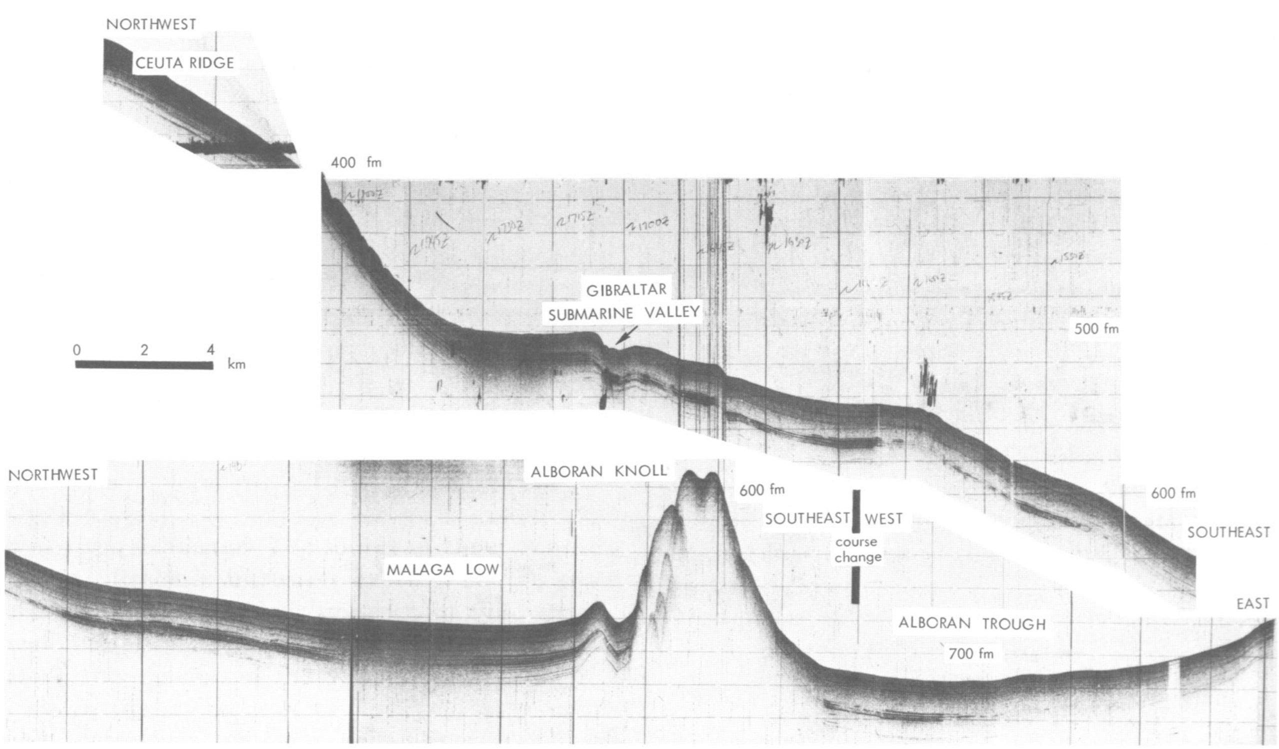

FIGURE 18.—High resolution subbottom profile (3.5 kHz) extending from the Ceuta Ridge near the Strait of Gibraltar downslope across the Alboran Basin. Traverse cuts diagonally across Gibraltar Submarine Valley, Málaga Low, and Alboran Trough (see Figure 1). (Spacing between horizontal lines is 20 fm (37 m).)

samples from this region. Tenuous evidence of more direct derivation from the north (region of Málaga-Marbella) is provided by the sands of core 107 collected south of Málaga in the Málaga Low (north of the Western Alboran Basin). The sands in this core display mineralogic attributes closely comparable to those in rivers draining the region north of coastal provinces F and G (Figure 5). It

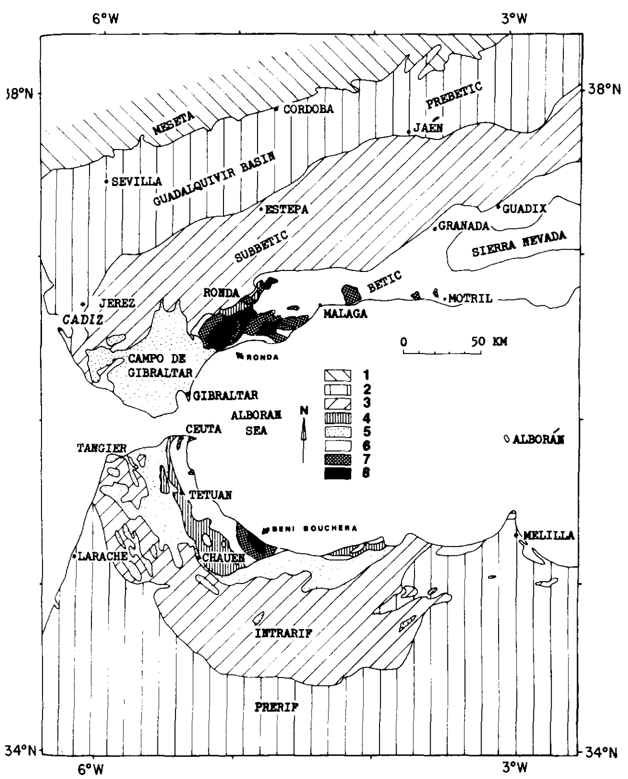

FIGURE 19.—General geology of region surrounding the Alboran Sea–Strait of Gibraltar region. Note general symmetric distribution of stratigraphic terrains around the Alboran Basin, including position of ultramafic rocks (Ronda and Beni Bouchera) on opposite margins. (1, Predominantly Paleozoic sedimentary, granitic, and metamorphic terrain of the Meseta. 2, Mesozoic and Tertiary zones of transitional depth clastic and carbonate deposition. 3, Mesozoic subbetic deep water carbonate, marl, and volcanic rocks; intrarif sandy flysch. 4, Spanish Rondaides and Moroccan Chaine Calcaire-Mesozoic carbonate rocks with Alpine-type facies in the Triassic. 5, Cretaceous and Tertiary sandy flysch. 6, Spanish Betic and Moroccan Paleozoic zones; Paleozoic geosynclinal clastic and thin Mesozoic carbonate rocks. 7, Andalusite-sillimanite low-pressure metamorphic sequences. 8, Ultramafic rock, including an outcrop near Ceuta. High-pressure metamorphic rock with kyanite is exposed in the Sierra Nevada uplift. Figure and legend after Loomis, 1972, fig. 1.)

is conceivable that these sands may have been conveyed directly offshore to this locale during periods of eustatic low sea level stands in the late Quaternary (Huang et al., 1972).

However, our analysis of the modern coastal sands demonstrates that a predominant transport from the Serranía de Ronda complex and adjacent regions directly to the deep sea is unlikely. Our evidence favors the transfer of Serranía de Ronda detritus southwestward toward Gibraltar and subsequent funneling to the Western Alboran Basin through the Gibraltar Canyon and Submarine Valley (Figure 23), a hypothesis suggested earlier by Huang and Stanley (1972). The trace of this transport path is recorded by sands of core 108 (lying 28 km southeast of Europa Point close to the Gibraltar Submarine Valley) that bear a marked mineralogic resemblance to the Alboran Basin sands on the one hand and the coastal sands of Province D (eastern shore of Gibraltar) on the other (Figure 5).

It should be noted that other source terrains and dispersal paths cannot be excluded for the older, deeper Western Alboran Basin sands. Thus, derivation from the north African margin and from the region east of Málaga during earlier geological periods remains a possibility which would require further examination and could now be identified on the basis of mineralogy. We can, however, exclude as a possible source area the Moroccan margin south of the NE-SW trending morphological barrier created by the Xauen-Tofiño-Alboran Ridge (Milliman et al., 1972).

In the broader context, the asymmetry of provenance of recent sands of the Western Alboran Basin plain indicated in this survey is a feature which at first sight would have been difficult to predict in view of the marked similarity of the opposite margins. The relief (Houston, 1964) as well as the geology of both margins are comparable and in certain respects mirror one another (Figure 19). Both areas are drained by relatively short, steep rivers flowing seasonally, and the spacing of these streams is similar on both the Spanish and Moroccan borders. Climatic conditions are comparable with rain concentrated during the winter months with 300 to 1400 mm per year on the Iberian margin (Figure 20) and 400 to 1400 mm per year on the Moroccan side (Jackson, 1961). Rainfall on both margins decreases toward

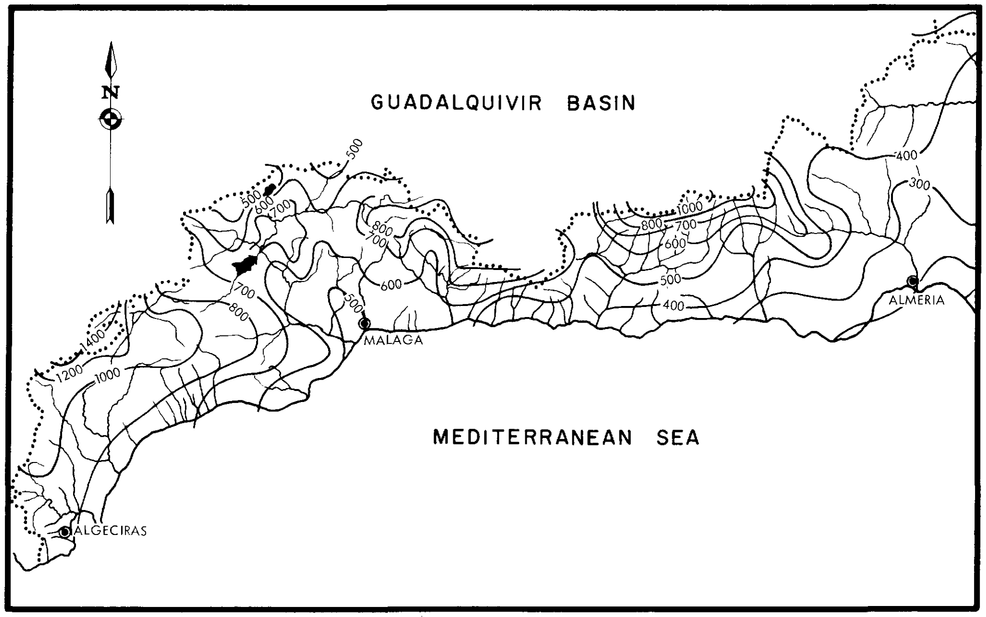

FIGURE 20.—Map showing rainfall distribution on the southern Spanish margin (contour interval, 100 mm/year). Maximum rainfall (1400 mm/year) occurs in the Sierra de Grazalema (headwater of the Guadiaro River) and in the Sierra Nevada (1000 mm/year). (Data after Centro de Estudios Hidrográficos, 1970.)

the east and in zones of lower elevations. It appears that intensity of river flow, at least on the Iberian margin, increases substantially toward the west, suggesting increased fluvial input of sediment in this sector. Although some major rivers are perennial, the majority are dry during much of the year (Figure 21). Snow melt derived from mountainous regions of the Sierra Nevada and the Rif may provide additional increments of sediment during the late winter and spring. Winds also are seasonally variable in both intensity and direction, but the strongest and most persistent aeolian transport is to be anticipated from the Sirocco, which is known to convey particles up to sand size (Figure 22) well offshore from the Moroccan coast (Ericksson, 1961).

The morphological symmetry of both margins of this part of the Mediterranean is further reflected in the submarine topography; narrow shelves (approximately 10 km wide to the 200 m isobath) leading to relatively smooth slopes of comparable gradients (less than 6°). Coastal currents also reflect this symmetry, showing a predominant westerly trend along both Moroccan and Iberian coasts* (Figure 11).

Despite these resemblances, this mineralogical study has enabled us to define the source and complex dispersal path of a deep-sea turbidite sand deposited in the intervening basin. The geometry of this and older sand bodies in the Western Alboran Basin plain, as determined by high-resolution subbottom surveys, had previously been defined (Bartolini et al., 1972) and a general input from the northwest postulated (Stanley et al., 1970). Moreover, a plausible source terrain of these sands, the Serranía de Ronda lying to the northwest, has

* It is noteworthy that predominant nearshore currents trend toward the west in the Western Alboran Sea in spite of the fact that the main direction of surface flow is to the east. This less saline surface and near-surface water mass, originating in the Atlantic, apparently produces large-scale jetlike eddies as it enters the Mediterranean east of Gibraltar (Gaibar-Puertas, 1967; Lucayo, 1969; Lanoix, 1974). Our study suggests that these eddies entrain a clockwise flow of water along the Moroccan margin and a counterclockwise movement along the Spanish coast.

FIGURE 21.—Photographs showing typical river beds which are dry during most of the year. *Upper:* Rambla de Albuñol, north of la Rábita and Punta Negra on the Spanish margin. *Lower:* mouth of Oued Ouringa, at Pointe des Pêcheurs on the Moroccan coast. (Note coarse bed load moved during flood stage.)

been identified on mineralogical ground (Bartolini et al., 1972; Huang and Stanley, 1972). The present study has refined these earlier surveys by enabling the complex transport path from source terrain to coast, through the nearshore zone and thence to the deep basin, to be defined by means of sediment composition.

Most previous heavy mineral studies of modern sediments in enclosed marine basins have been concerned either with relatively shallow areas, in which depositional processes differ greatly from those operative in the Alboran Sea (van Andel and Postma, 1954), or with deeper basins differing in important morphological respects from the present study area. Certain of the latter category differ in possessing bordering areas of low relief (Baak, 1936; Hsü, 1960; Davies and Moore, 1970), while others, although bordered by mountainous regions, receive an important part of their filling sediment from one end of the elongate trough, usually from a major deltaic source (van Andel, 1964; Pigorini, 1968).

Our study suggests that there exists yet another type of elongate basin bounded by regions of high relief which *a priori* could supply material of varied source directly to the adjacent deeps, thus conforming to a multisource basin model (Pettijohn, 1957; Pettijohn et al., 1973). However, the evidence presented above suggests that during the recent geological past, the dispersal patterns within this basin have been essentially longitudinal, i.e., input from the western termination. In view of the possible reversal of currents on the Strait of Gibraltar (with eastward flowing bottom currents below a westward surface outflow), it is probable that this longitudinal transport pattern was reinforced during glacial lowstands of the Pleistocent (Huang et al., 1972).

FIGURE 22.—Sirocco blowing silt and sand seaward on the Moroccan coast near Pointe des Pêcheurs (April 1973).

Elongate deep marine basins with predominant longitudinal transport patterns are common in the geological record. Various interpretations of the dispersal systems in such troughs, including elongate flysch basins, have been proposed (Kuenen, 1958; Pryor, 1961). In geological terms, our study demonstrates the importance of the mineralogic changes produced by coastal processes and the further modification, largely due to size-sorting, which ensues from downslope transport to the final site of deposition. Changes induced by marine transportation appear to have a more pronounced effect on the light mineral fraction, while even relatively unstable heavy mineral species (such as orthopyroxene) apparently suffer less modification. This conclusion must be qualified for geological purposes by the observation that many heavy mineral species are susceptible to diagenetic alteration and removal (van Andel, 1959).

A further geological implication of our study is

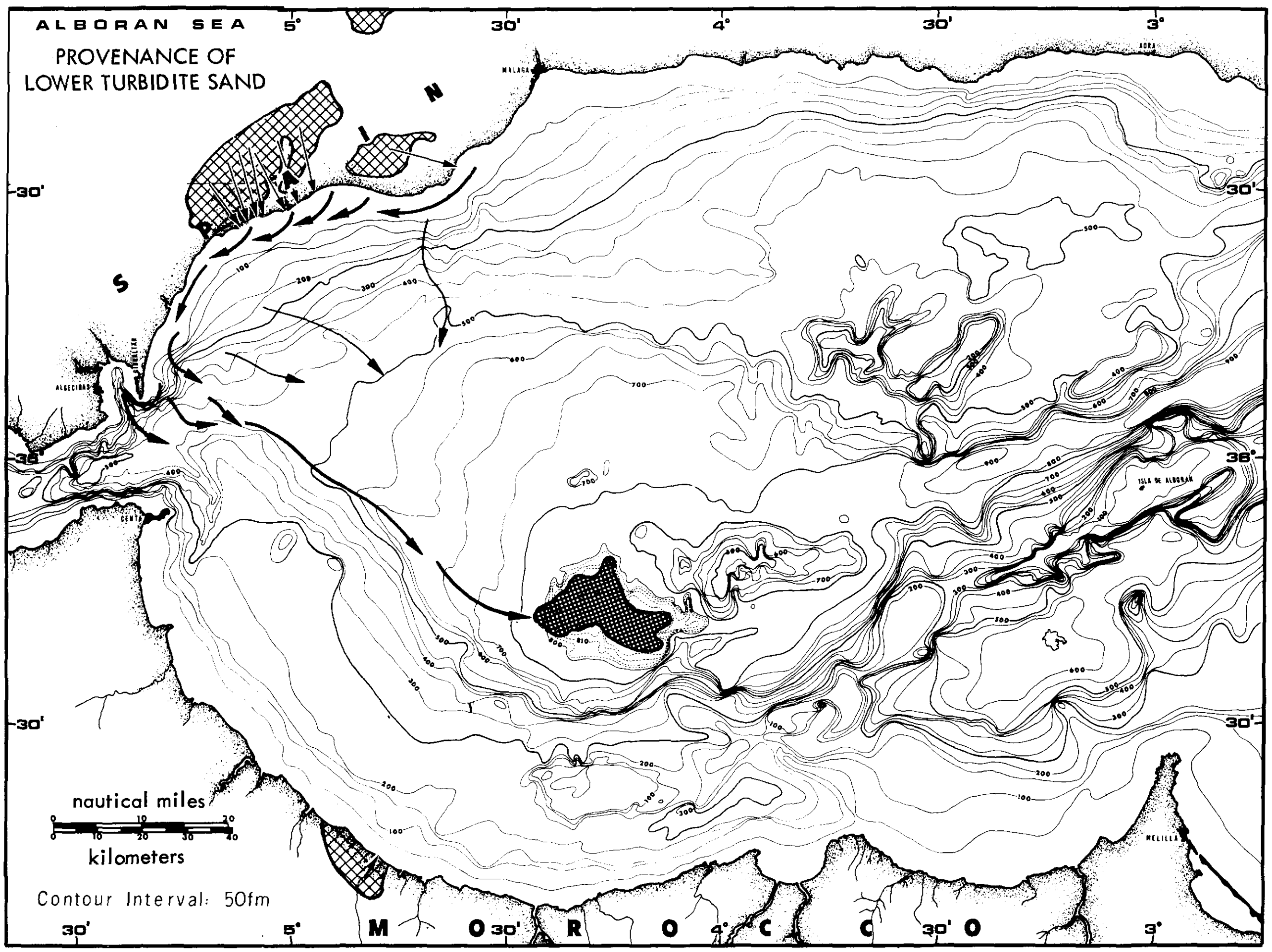

FIGURE 23.—Summary diagram showing provenance and complex dispersal path of sands that were deposited as the *Lower sand-and-silt layer* (Huang and Stanley, 1972) in the Western Alboran Basin (dark pattern shows extent of this layer in the basin plain—after Bartolini et al., 1972) at the end of the Pleistocene. These sediments, eroded from the Serranía de Ronda region, were transported by rivers to the coast between Estepona and Marbella. The sands were subsequently reworked to the southwest by coastal currents to the Strait of Gibraltar region, and then downslope toward the southeast by turbidity current through the Gibraltar Submarine Valley.

that the path taken by detritus from source terrain to the final site of deposition may be highly complex and is largely governed by processes active in the coastal zone, a region seldom preserved in ancient mobile belts.

Summary

1. This study defines the composition and regional distribution of the major sand-sized light and heavy mineral groups on the Iberian and Moroccan margins of the Alboran Sea, an almost totally land-enclosed, mountain-bounded basin in the western Mediterranean.

2. Twenty light and heavy mineral provinces are identified along the basin margins and these are broadly concordant with the limits of the major drainage basins. The concordance emphasizes the close relationship which exists between the varied lithology of the mountainous Moroccan Rif and the southern Iberian Betic margins, and the mineralogical composition of sediments on the adjacent coast.

3. Sands in the coastal and fluvial samples can be related to specific source terrains. Two major mineralogical sectors (comprising 13 mineralogical provinces) are recognized on the Spanish margin: one between Velez-Málaga and Adra, influenced by the Nevado-Filábride and Alpujárride complexes; the other west of Málaga draining the ultrabasic rocks of the Peridotite complex. Two major mineralogical sectors (comprising 7 mineralogical provinces) are also recognized on the Moroccan margin: one from the Beni Bouchera ultrabasic complex to the east, influenced by Paleozoic, Mesozoic, and Tertiary sediments; the other north and west of the ultrabasic complex, draining Paleozoic sediments, metamorphic rocks, and basic or ultrabasic intrusives.

4. A special study of samples from six rivers in the western sector of the Iberian margin west of Marbella shows that river samples closely reflect the lithology of the terrain traversed. River samples and samples collected on the coast adjacent to the appropriate river mouth are broadly comparable in composition, attesting to the virtual direct transport of sediment from source to sea on all margins of the Alboran Sea. Differences between fluvial and coastal samples may be a function of differing hydraulic processes and also possibly grain-size factors.

5. That modification of the mineralogy occurs while the sediment is held in the littoral and nearshore zone is demonstrated by the nonconcordance in detail of mineral province boundaries with adjacent drainage basin boundaries. The mineralogical variation from river to river is greater than along the intervening stretch of coast near the river mouths. The greater sample-to-sample similarity along the coast indicates that at least some mixing and dilution of river supply has occurred at the coast as a result of longshore current transport.

6. The lateral trends observed within Moroccan and Spanish coastal mineralogical provinces provide evidence on the actual sense of nearshore sediment transport. The mineralogical trends suggesting predominant nearshore transport directions (movement largely to the west along extensive sectors of both the western Spanish and Moroccan margins) are substantiated by independent evaluation of coastal current motion and long-term sediment drift patterns observed from aerial photographs.

7. Lateral variations in mineralogical trends may also be partly a function of the increased contribution from coastal outcrops and partly to less constant coastal drift patterns (area east of Málaga for example). Furthermore, local coastal morphological factors and meteorological conditions that vary seasonally influence the distribution of mineral assemblages. These factors, as well as nearshore currents, operate to concentrate or dissipate specific minerals of differing size, density, or physical durability.

8. Several possible interpretations are provided for the origin of the mineral suites in the coastal sands of the Bay of Algeciras. However, the present mineralogic distribution within the Bay conforms closely to predicted counterclockwise transport paths.

9. This mineralogical study enables us to define the source and dispersal of sands to the intervening deep basin in spite of the geological and geographic similarities that characterize the opposite margins of the Alboran Sea. A comparison of sands collected in cores in the Western Alboran Basin with sands on the Alboran coastal margins serves to identify the ultimate source of late Quaternary and Holocene sands in the deep basin plain.

Sources east of Marbella on the Spanish margin as well as on the Moroccan margin can be precluded. Heavy minerals indicate that the ultimate derivation lies in the Serranía de Ronda complex in the western Betic chain as postulated in earlier studies.

10. The dispersal path of sands between the Serranía de Ronda source to deep basin is a complex one. We suggest that detritus was first transferred southwestward toward Gibraltar by coastal agents and then subsequently was funneled to the Western Alboran Basin through the Gibraltar Canyon and submarine valley.

11. It appears that mineralogical changes produced during dispersal by marine processes have a more pronounced effect on the light mineral fraction, while even relatively unstable heavy mineral species apparently suffer less modification. The implication of this study is that there is a marked mineralogical evolution of detritus moving between source and deep basin, and that these changes are largely governed by processes active in the coastal zone, a region seldom preserved in ancient mobile belts.

12. In geological terms, the Alboran Sea can serve as one type of model for sedimentaion in an elongate, enclosed basin bounded by regions of high relief. Although this region, a priori, would conform to a multisource basin model, we show that the dispersal pattern within the basin has been essentially longitudinal. Unlike some elongate basins in the geological record, filling from one end has been from currents (input at the Strait of Gibraltar) and not from a major delta point source.

Appendix

Brief Summary of the Betic Cordillera Source Terrains

The Betic Cordillera, a highly complex mountain chain, can be discussed most readily in terms of major stratigraphic-structural units. Two major zones are recognized, i.e., an Internal Zone and an External Zone. The major units described in the following sections are depicted in Figure 2.

Internal Zone

The major stratigraphic-tectonic units in the Internal Zone include the *Nevado-Filábride Complex* (unit 2, Figure 2), *Alpujárride Complex,* eastern sector (units 3–7), *Casares Unit,* Alpujárride, western sector (unit 10). The *Malágiude Complex* (units 8 and 12), *Peridotite Complex* (unit 1), and two other units—*Sierra Blanca Unit* (unit 9) and *Las Nieves Unit* (unit 11)—whose attribution to a specific complex is not clear—are also included in the Internal Zone.

Nevado-Filábride Complex.—Rocks of this unit crop out extensively in the Sierra Nevada and its prolongation toward the east. It comprises three tectonic-lithological units.

The Sierra Nevada Series.—Composed largely of graphite-bearing micaschists (in large part garnetiferous) with intercalations of quartzites. Quartz, sodic plagioclase, garnet, white micas, biotite, tourmaline, zircon, rutile, and opaque minerals form the predominant mineral assemblage. Locally, amphibolites are present and these contain hornblende, actinolite, epidote, quartz, mica, and tourmaline.

The Filábride Series.—The Filábride Series, more varied in composition than the one described above, include micaschist, quartzite, marble, gneiss, and amphibolite. The micaschists contain the same minerals as in the Sierra Nevada Series as well as staurolite, epidote, kyanite, and muscovite. Gneiss includes quartz, albite, oligoclase, biotite, epidote, garnet, and chlorite. Amphibolite contains various amphibole minerals, chlorite, epidote, quartz, mica, and clinopyroxene.

The Caldera Unit.—This unit contains similar mineralogical assemblages as those in the Filábride sequence listed above.

Alpujárride Complex.—This complex includes strata of Paleozoic and Triassic age. Four major lithostratigraphic units are recognized.

The Paleozoic formations include micaschist and quartzite (depicted as unit 3 on Figure 2); these, in their lower part and toward the west, change facies and become dolomitic marble with lenses of amphibolite (unit 4). The micaschist includes quartz, sodic plagioclase (albite-oligoclase), white micas, biotite, and locally (in some stratigraphic-tectonic nappe units) andalusite, staurolite, chlorite, chloritoid, garnet, and epidote (pistacite and zoisite). Dolomitic marble as well as dolomite include calcic amphiboles (tremolite and actinolite), feldspars (albite, oligoclase), biotite, muscovite, and phlogopite. Amphibolites, which appear related to the recrystallized dolomites, include minerals of the type found in the amphibolites of the Nevado-Filábride Complex (see above).

The Permo-Werfenian Formations (unit 5) include lower grade metamorphic phyllites and quartzites. Quartz, albite, muscovite, chlorite, tourmaline, and zircon are the most common minerals.

The Middle and Upper Triassic formations (limestone and dolomite, partly recrystallized but without the metamorphic mineral suite (unit 6)) contain metallic sulfides and oxides related to sedimentary or hydrothermal processes, or both. Quartz, calcite, fluorite, epidote, and hematite occur in hydrothermal veins.

Maláguide Complex.—Two lithostratigraphic units are recognized: a lower one, distinctly metamorphic of possible pre-Cambrian age, and an upper one, consisting of Paleozoic strata (locally, with a poorly developed Mesozoic-Tertiary cover), which is essentially sedimentary. The base of the Pre-Cambrian (?) rocks consists of gneiss and micaschist. Gneisses dominate the base of the sequence; they are leucocratic, containing quartz, plagioclase, microperthite, microcline, and also sillimanite, garnet, and low amounts of cordierite. Above these are found micaschist and micaceous gneiss with garnet, sillimanite, staurolite, plagioclase, and microcline.

The Paleozoic rocks (unit 12, Figure 2), regionally, are lithologically extremely variable. Rocks displaying low-grade metamorphism (phyllites and micaschists with quartz, white mica, biotite, garnet and andalusite) occur at the base of the section. The bulk of the unit comprises sedimentary series, including flysch-type sequences that have undergone considerable diagenesis, but without the formation of metamorphic minerals; interbedded carbonates are also common. The Permian-Mesozoic-Tertiary cover, which is only locally preserved, includes limestone and sandstone.

Peridotite (ultrabasic) Complex.—Ultrabasic plutonic rocks crop out extensively west of Málaga and form the Peridotite Complex of the Serranía de Ronda. In this region are found dunite and harzburgite and, less frequently, pyroxenite, norite, gabbro, lherzolite, and websterite. In many places, these rock types have been partially, or totally, serpentinized. Dominant minerals are olivine, orthopyroxene, clinopyroxene, calcic and calco-sodic plagioclase, apatite, spinel, and opaque minerals.

Sierra Blanca Unit.—This group of rock types (unit 9) has been affected by medium to high-grade metamorphism and is in part similar to the Casares Unit described below. Marble and gneiss are dominant, and amphibolites are also locally present. Marbles are to a large degree totally, or partially, dolomitized. The biotite gneiss contains sillimanite, cordierite, and/or andalusite, depending upon the locality.

Casares Unit.—This group of rock types (unit 10) of the Alpujárride Complex (western sector) comprises essentially Paleozoic metamorphics overlain by limestone and dolomite, marbleized, of Triassic age. The base of this metamorphic sequence is related to the Peridotite Complex, their mutual contact being intrusive. From older to younger, the following types occur: gneiss, rich in feldspar, cordierite and, locally, garnet; micaschist with andalusite, which in its lowest parts contains garnet, staurolite and biotite; phyllite and quartzite, with similar minerals as those in the Permo-Werfenian rocks of the Alpujárride Complex (eastern sector); limestone and/or dolomite, marbleized, similar to the Middle and Upper Triassic of the Alpujárride Complex (eastern sector).

Nieves Unit.—Carbonates of the Upper Triassic and Lias (unit 11) are assigned to the Internal Zone by some authors and to the External Zone by others. Limestone, partially dolomitized, is the dominant lithology; abundant chert nodules are present locally.

External Zone

A number of units including the Campo de Gibraltar, "Flysch" de Colmenar, and the Subbetic Zone are included in the External Zone. Each of these sequences can be characterized by specific lithological criteria; the age of each unit has also been determined. Three major groups are differentiated: a detrital red bed facies of Triassic age, a Jurassic limestone-dominated facies, and a marl-rich Cretaceous-Paleogene-Lower Miocene sequence.

Triassic Units.—The sediments comprising this group (unit 13, Figure 2), very different from the Triassic of the Internal Zone, display a "Germanic facies" aspect. The predominant lithologies include variegated clay, marl, and sandstone. Locally dolomite and ophite are exposed as well as evaporite (in particular gypsum and salt). These crop out in numerous areas and are easily eroded.

Jurassic Units.—Sedimentary rocks of this group (unit 14) include a highly variable suite of sediments, and show a great variability in thickness (González-Donoso et al., 1971). The dominant lithologies include limestone of highly variable texture and marls and petrologic transitions between the two. Very locally, there are notable outcrops of radiolarites and submarine basic volcanics (pillow lava) intercalated in the Jurassic series.

Cretaceous-Paleogene–Lower Miocene Units.—This suite of sedimentary rocks (unit 15) includes, for the most part, marl and marly limestone facies. There are recognizable lithologic variations that are related to differences in age, outcrop locality, and tectonic grouping. A flyschoid facies with sandstone (includes rocks of different ages) dominates toward the west; toward the east, on the other hand, marl and limestone intercalations are common.

Post-Orogenic Sequences

The extensive outcrops of sediments of Neogene-Quaternary age that fill postorogenic depressions and recent alluvial basins are designated as Post-Orogenic Sequences on the map (unit 16). The most common lithologies of Neogene age are conglomerates, sandstones, shales, and evaporites. Limestone and bioclastic rocks also crop out locally. Quaternary sediments include large volumes of detrital material of medium to coarse grain size.

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