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PETROLOGY AND GEOCHEMISTRY OF MODERN DETRITUS DERIVED FROM A RHYOLITIC TERRAIN, WESTERN CHIHUAHUA, MEXICO

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RESUMEN

Se estudiaron petrográfica y químicamente las arenas del primer ciclo de los arroyos que drenan una pequeña porción de la Sierra Madre Occidental del occidente de Chihuahua. Los detritos derivados de este terreno semi-árido y montañoso, formados casi completamente por toda riolítica, no están intemperizados y forman una arenita lítica inmadura. Los fragmentos de roca riolítica varían entre el 45 y 69% de la fracción. Este detrito se comparó petrográficamente con otras 18 arenas volcaniclásticas, de origen erosional, de la región circumpacífica y se especula su composición en los ciclos sedimentarios futuros.

ABSTRACT

First cycle sands in streams draining a small portion of the Sierra Madre Occidental of western Chihuahua were studied petrographically and chemically. Detritus derived from this semi-arid, mountainous terrain, one underlain almost completely by rhyolitic tuff, is unweathered and forms a strikingly immature lithic arenite. Rhyolitic rock fragments range between 45 and 69 percent of the framework fraction. This detritus is petrographically compared with 18 other volcaniclastic sands of erosional origin from the circumpacific region and its composition in future sedimentary cycles is speculated.

INTRODUCTION

Petrographic studies of sediments rich in volcanic debris are much less numerous than those derived from granitic, metamorphic and cratonic terrains. In part, this may represent a historical accident in that sedimentary petrology

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had its beginnings in regions remote from active volcanism; in part, this may reflect an initial tendency for sedimentary petrologists to leave such deposits to others. Nonetheless, many of those who have considered the fill of geosynclines have not been hesitant to hypothicate that volcanism contributed importantly to geosynclinal fill —if not first cycle debris, certainly second or third cycle. Unfortunately, however, actual studies of composition and chemistry of modern sands from streams eroding volcanic terrains are but few in number. Here we report on composition and chemistry of the detritus in streams draining a small portion of a vast Tertiary volcanic terrain that stretches from central Arizona southeastward to Mexico City, a distance of almost 2400 km (Figure 1). Rhyolitic tuffs and tuff breccia predominate. A conservative estimate of the volume of this deposit is 400,000 km^3 which certainly qualifies it as a major event in the tectonic development of the circumpacific region and also as a major source for detritus that fills nearby intermontaine basins and later finds its way to bordering coastal plains and finally to the marine shelf and slope of the continental margin.

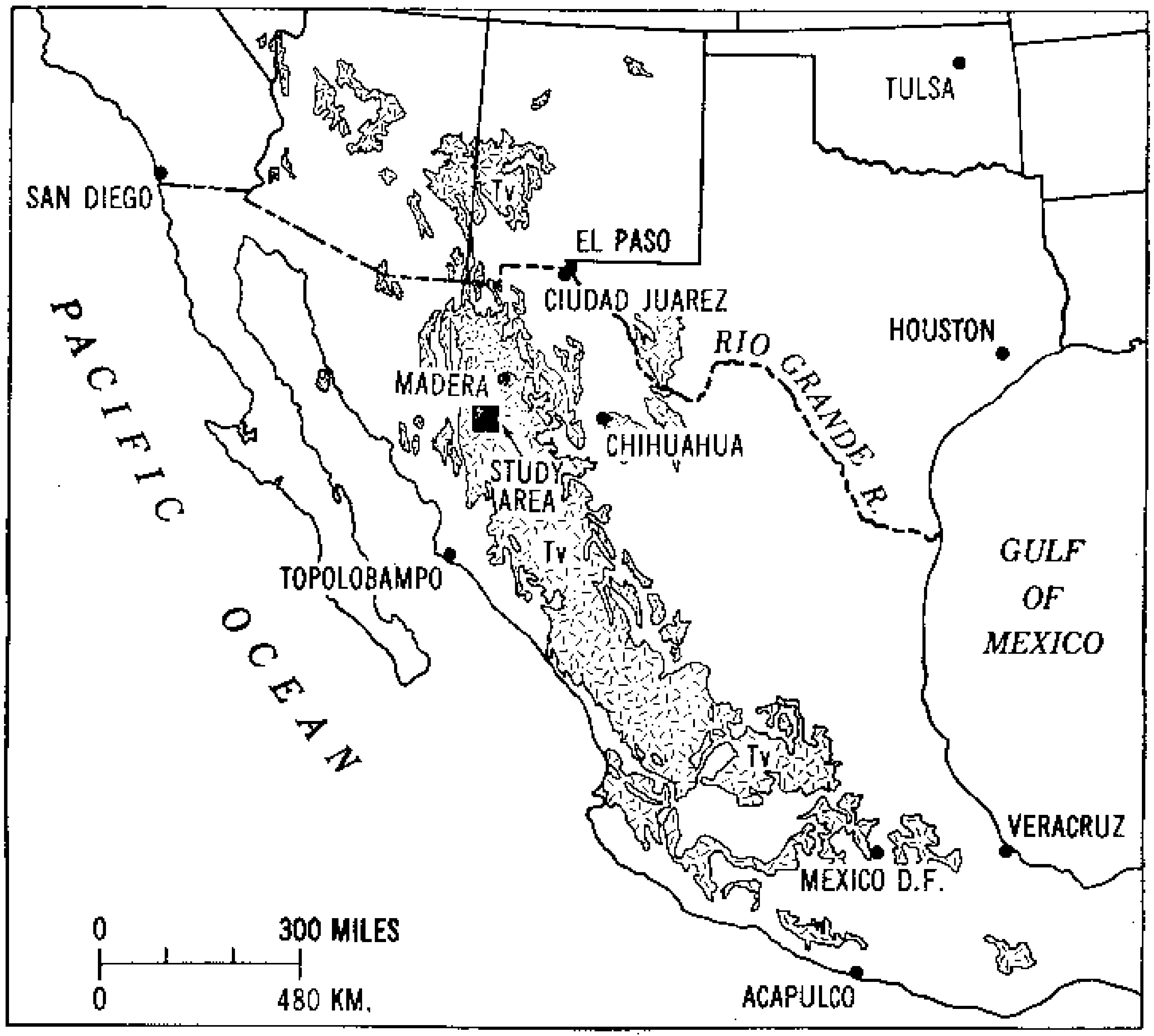

FIG. 1.—Tertiary volcanics (Tv) and study area.

REGIONAL SETTING

The study area southwest of Madera lies within the Sierra Madre Occidental physiographic province, which is roughly contiguous with the area of volcanics shown in Figure 1. The rocks of this province are gently-dipping to flat-lying middle Tertiary rhyolitic and andesitic tuffs interbedded with some flows, conglomerates and volcanic sandstones. Rhyolitic tuffs predominate and impart a prominent sedimentary layering to the landscape (Figure 2). Some idea of the predominance of rhyolitic tuff is obtained by boulder counts from the streams of the area, a typical count of 311 yielding the results of Table 1. Collectively, these volcanics attain thicknesses between 1300 and 1600 m but thin in the western part of the province. The youngest volcanics are basalts whose volume is small, however, in comparison to that of the rhyolitic tuffs. These volcanics rest with unconformity upon folded and deformed Paleozoic and Mesozoic limestones, shales, and quartzites. Some small andesitic porphyries, diorites, and granites intrude the sequence, but in comparison to the rhyolitic tuffs, they are volumetrically negligible and none are known in the study area. A summary of the region's geology is given by King (1939). In 1943 Sidwell and Renfroe published a description of sands in streams to the north of our area, roughly halfway between Madera and El Paso, Texas.

TABLE 1.—Compositon of El Nogal Point bar gravels.

(54 to 130 mm)

Lithology	Percentage
Rhyolitic tuff	63
Rhyolitic tuff breccia	19
Rhyolite	7
Tuff	3
Basalts	5
Pitchstone	1
Vein quartz	2
Total:	100

Beginning with late Tertiary uplift a hig plateau was formed which today has elevations between 1650 and almost 2400 m. Dissection is deepest where Pacific drainage has cut deep headward gorges, some with local relief rivaling that of the Grand Canyon and its tributaries. This dissection has produced a youthful to mature topography with narrow, flat-bottomed valleys. Local relief commonly varies from 600 to 900 m. East to the Pacific

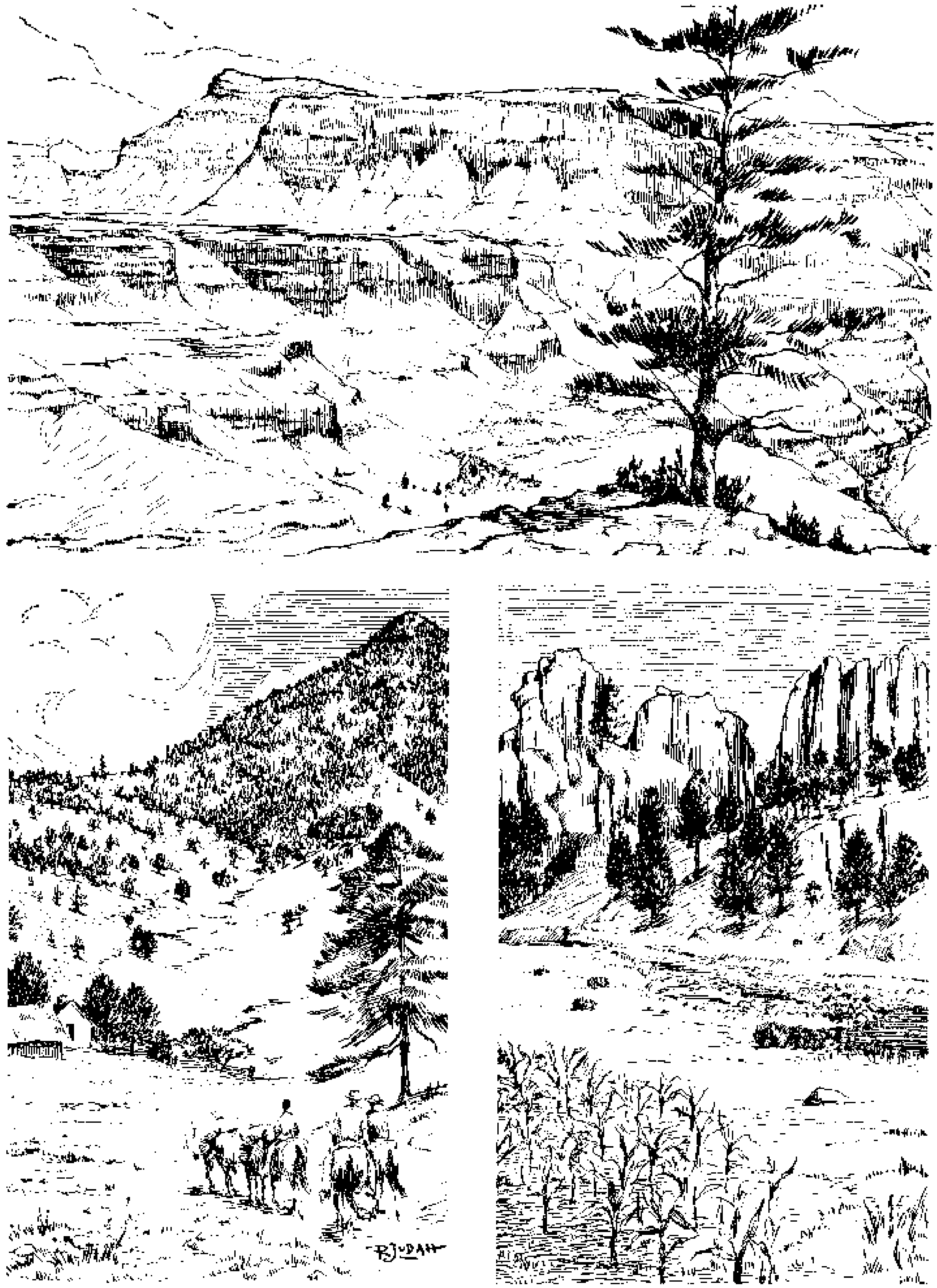

Fig. 2.—Some typical topography developed on the volcanic rocks of the semiarid Sierra Madre Occidental in western Chihuahua. Note "sedimentary" layering of tuff flows (above) and characteristic weathering of a single, massive, ash flow tuff (lower right).

drainage the topography is somewhat more subdued and is in maturity. Figure 2 shows some of the typical topography of the region.

Soil development closely correlates with topography. On ridge tops and areas of steep slopes, soil is scant and consists of thin, scattered, azonal lithosols, chemically little different from parent material. But on lower slopes and valley bottoms, thicker, fertile soils are present.

The climate in the study area is semi-arid except for the higher mountain slopes, which support pines. Annual precipitation is in the neighborhood of 40.5 to 72.5 cm (20 to 25 inches), three fourths of which falls in July, August, and September commonly as afternoon thunderstorms and often with torrential rainfall and hail. The median annual temperature is between 14 to 17°C.

The samples we studied, seven in all (Table 2), came from an area of some 4000 km^2 in the districts (municipios) of Temosachic and Ocampo of southwestern Chihuahua and were obtained from the Yepachic, Concheno, Tutuaca, and Temosachic Rivers all of which feed the Mayo and Yaqui Rivers, the two major streams that empty into the Gulf of California.

TABLE 2.—Sample locations

Sample No.	*Stream*	
1	Rio Yepachic	District of Temosachic
2	Río Concheno	District of Ocampo
3	Rio Tutuaca	District of Temosachic
4	*El Nogal*	*District of Temosachic*
5	Arroyo Pescado	District of Temosachic
7	Rancho El Nogal	District of Temosachic
10	Rio Temosachic	District of Temosachic

PETROGRAPHY AND CHEMICAL COMPOSITION

GENERAL CHARACTERISTIS.—The most striking feature of these sands is their compositional and textural *immaturity*. The sand fraction is dominated by unaltered rhyolitic volcanic rock fragments, fresh idiomorphic feldspar grains and whole or broken phenocrysts of volcanis quartz. Some of the material we call rhyolitic tuff may in fact be ash flow. However, our petrographic examination of the sand fraction revealed very little material which could be classified as ash flow. The samples are best described as moderately sorted, medium grained, angular sand. Silt and clay sized particles are scarce ranging from 1 to 6 percent, averaging only 3 percent. Tables 3 and 4 summarize these characteristics.

METHODS.—To estimate modal composition, 300 point counts per sample were performed on thin sections made from a resin-impregnated fraction of

TABLE 3.—Compositional and textural characteristics

Mineralogy	1	2	3	4	5	7	10	Average
Quartz	12.4	16.0	20.0	13.0	25.8	21.0	15.5	17.6
Potash feldspar	7.1	11.0	9.0	11.0	8.1	17.0	9.0	10.3
Plagioclase feldspar	8.6	8.0	6.0	7.0	4.6	10.7	8.0	7.5
Rock fragments	69.0	52.4	53.5	63.0	60.0	45.0	58.0	57.2
Heavy minerals	2.3	12.0	11.5	6.0	1.5	5.3	9.3	6.8
Matrix	3.0	2.0	3.0	3.0	4.0	6.0	1.0	3.1
Texture (ϕ units)								
Mean size	2.26	1.40	1.67	1.93	1.16	1.01	0.94	1.48
Sorting	0.77	0.82	0.73	0.83	0.96	1.99	0.58	0.95
Skewness	+0.12	+0.07	+0.37	+0.10	+0.40	+0.33	—0.42	+0.12

TABLE 4.—Composition *versus* roundness

Figures in percent

	Very angular [1]	angular[2]	Sub angular[3]	Sub rounded[4]	rounded[5]	Well rounded[6]
Quartz	7.0	38.7	44.3	9.0	0.8	0.0
Feldspar	13.8	40.7	40.4	4.9	0.0	0.0
Rock fragments	14.7	40.5	39.7	4.1	0.8	0.0

each sample. The mineralogic composition of the silt and clay fraction was determined by x-ray analyses of powdered samples. The angularity of quartz, feldspar and lithic fragments, as defined by the Powers Roundness Scale, was estimated by 100 counts per sample. Size frequency distribution characteristics for each sample were determined from mechanical analyses employing a half phi interval sieve set.

QUARTZ.—Following Blatt and Christie (1963, p. 564-565) and Blatt (1967, p. 402-403) quartz grains were classified on the basis of their extinction characteristics and polycrystallinity (Table 5).

TABLE 5.—Quartz varieties

Defining property	Percentage
Nonundulatory extinction (Monocrystalline quartz)	89.2
Undulatory Extinction (Monocrystalline quartz)	6.5
Polycrystalline quartz	4.3

The most noteworthy result of this analysis is the overwhelming abundance (96%) of monocrystalline quartz grains and the high incidence (92%) of nonundulatory extinction among the monocrystalline grains. In addition to their characteristic nonundulatory extinction, monocrystalline quartz grains display some distinctive external features. The majority of grains in the coarse to medium sand range are broken phenocrysts, *i.e.*, individual grains are bounded by both crystal faces and smooth curving fracture surfaces. In thin section these grains are virtually free of inclusions and therefore have a water-clear appearance. Nearly all are fractured and patches of glass or devitrified glass cling to many of them. A lesser number of grains recognizable as broken phenocrysts were observed among the medium grained quartz particles but no such individuals were identified from the fine sand and coarse silt fractions. Individual grains in the finegrained quartz assemblages are very angular, commonly triangular or elongate, in outline, and show no sign of abrasion.

Glass-filled marginal embayments and "inclusions" are present on about 10 percent of the grains (Figure 3) and are most common in the coarser sizes. The proportion decreased steadily in the finer sizes and none were recognizable in the fine sand and silt fractions.

Polycrystalline quartz amounts to only 4 percent of the total quartz. In contrast to the monocrystalline quartz, polycrystalline quartz is anhedral, lacks marginal embayments and generally seems less fractured. Variations in the alignment of individual crystal domains, extinction characteristics and interdomain boundaries allowed us to distinguish two kinds of polycrystalline quartz. Twenty five percent of the grains are characterized by a parallel to subparallel alignment of strongly undulatory crystal domains. Intercrystalline boundaries are sutured. Orientation of domains in the remaining 75 percent is random, interdomain boundaries are smooth-curved or planar and extinction is nonundulatory.

From our observations of the quartz assemblage of these river sands the following facts emerge.

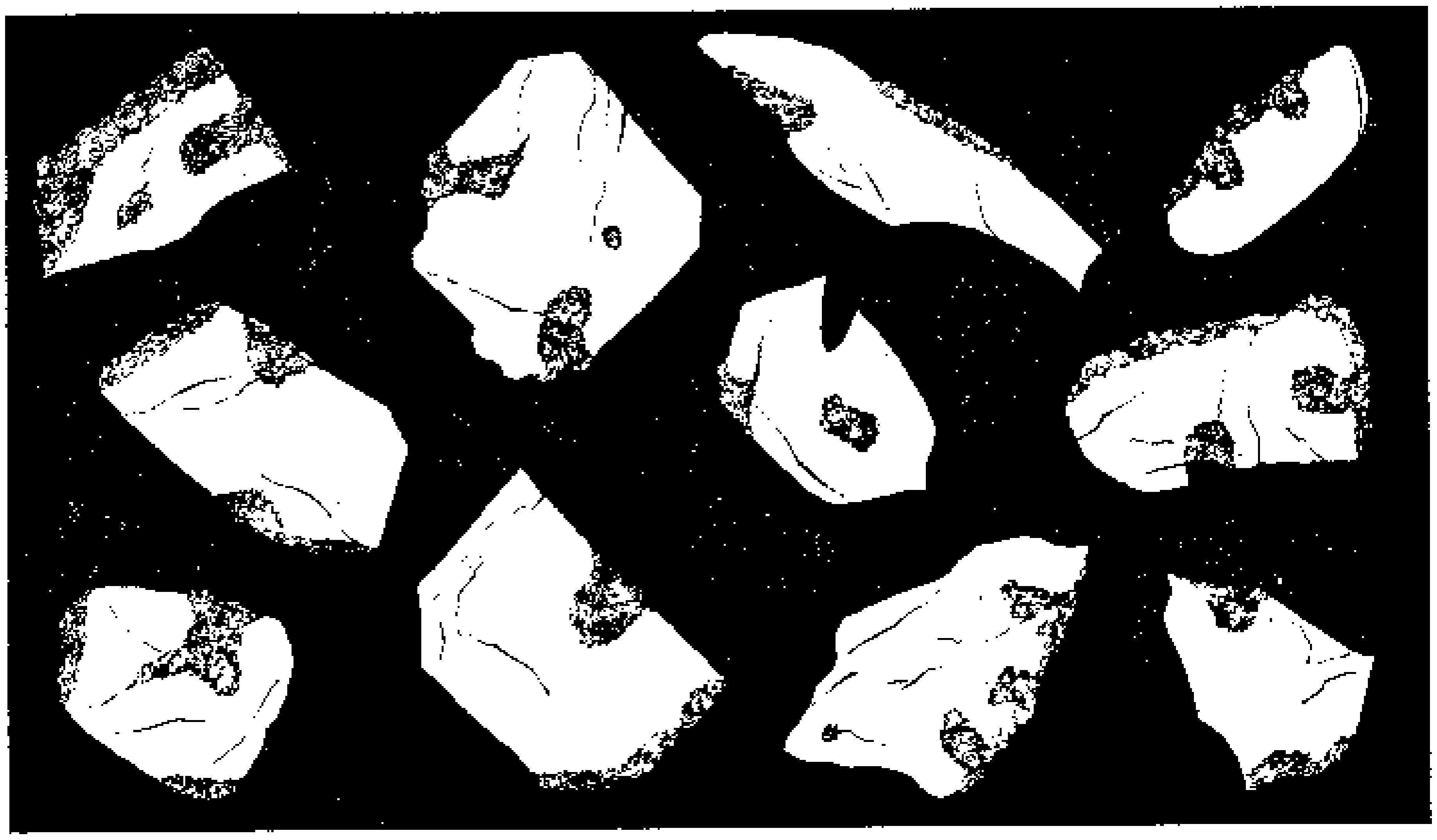

FIG. 3.—Composite of monocrystalline quartz grains showing typical volcanic features — embayments, fractures and glassy inclusinos.

1) The overwhelming majority of grains are monocrystalline units displaying nonundulatory extinction.
2) Grain morphology is strongly size dependent — the coarse and medium size fraction is dominated by fragments of internally fractured phenocrysts, whereas the fine and very fine size fractions are characterized by anhedral, very angular fragments lacking internal fractures.
3) Glass filled marginal embayments are present on about 10 percent of the grains in the coarse and medium sand fractions and are much less numerous in the fine and very fine sand fractions.
4) Quartz grains ranged in size from 1.5 mm to less than 0.06 mm.

FELDESPAR.—Fresh, angular fragments of both potash and plagioclase feldspar phenocrysts are present in each sample. Glass-filled marginal embayments are present on about 5 percent of the grains. Total feldspar content varies from 13 to 28 percent and averages 17 percent, almost identical to that of quartz (Table 3).

Nearly all the potash feldspars, which, with one exception, form the majority of the feldspar assemblage (Table 3), are untwinned, commonly zoned, show a biaxial negative interference figure with a 2v ranging from 15° to 25° and are most likely sanidine. Refractive index determinations revealed that the most common types of plagioclase are oligoclase and andesine. Albite was observed, but rarely. Characteristically the plagioclase is twined according to the albite or pericline twin laws Zoning was observed but is not common. Inclusions are generally lacking and no perthitic intergrowths were seen.

HEAVY MINERALS.—Among the samples analyzed the proportion of heavy minerals varied from 1.5 to 12.0 percent. Generally this assemblage was concentrated in the 2.5 and 3.0 phi (Φ) size classes, however, in samples 2 and 3 magnetite and biotite were also present in the 1.0 and 1.5 phi (Φ) size classes. Magnetite and magnetite-illmenite intergrowths, accounting for 70 percent of the heavy mineral suite, occur as unaltered, well rounded to subangular grains. Glassy or aphanitic rims adorn about 15 percent of these grains. Amphiboles average 13 percent. Common brown hornblende forms nearly 30 percent of this amount. The remaining 70 percent is basaltic hornblende. This variety has a distinctive dark reddishbrown body color and is prismatic in form. Augite, hypersthene and biotite, present in roughly subequal amounts, total 12 percent. Sphene, zircon, pyrite, apatite and limonite constitute the remaining 5 percent of the heavy mineral suite.

ROCK FRAGMENTS.—The most abundant grain in each sample are rock fragments, accounting for 45 to 69 percent of the detritus. Of the lithic constituents rhyolitic tuff predominates (71%). The majority of these (82%) are crystall tuffs, consisting of numerous idiomorphic grains of quartz and feldspar, rare idiomorphs of pyroxenes, amphiboles, magnetite and biotite set in a holohyaline to holocrystalline matrix. Most of the crystal tuffs are *microbreccias* (Figure 4), *i.e.*, idiomorphic grains haphazardly arranged in a fine grained to glassy matrix. Alternation is minimal. Among the phenocrysts, alteration products are present as 1) thin clay seams on cleavage surfaces of a few feldspars, 2) vermiculite growths on some biotite crystals, and 3) reddish brown jackets on a few opaque ore grains. The aphanitic matrix appears to be composed primarily of quartz and feldspar. Clays and zeolites usually make up less than 5 percent of the matrix of the crystal tuff fragments.

The remainder (18%) of the rhyolitic tuff assemblage consists of vitric tuff fragments (Figure 4). Texturally, these fragments are characterized by a matrix of glass dust crowded with shards and other glass chips. With the exception of thin microcrystalline rims bordering a few of the shards, alteration products are notably absent. Index of refraction of the vitric tuff ranged from 1.495 to 1.520.

The remaining volcanic detritus totaling 26 percent of the rock fragment assemblage, is characterized by grains of porphyritic andesite, dacite and rhyolite and by aphanitic grains displaying spherulitic or plumose textures (Figure 4). Fluidal banding, produced either by parallel alignment of phenocrysts or by trains of glass blebs, crystalites or bubbles in the matrix, is a common feature of the andesite grains.

Only 3 percent of the rock fragments appear to be nonvolcanic in origin.

CLAY AND SILT.—To determine the mineralogy of the silt and clay sized particles, two samples of overbank mud were analyzed, using standard x-ray

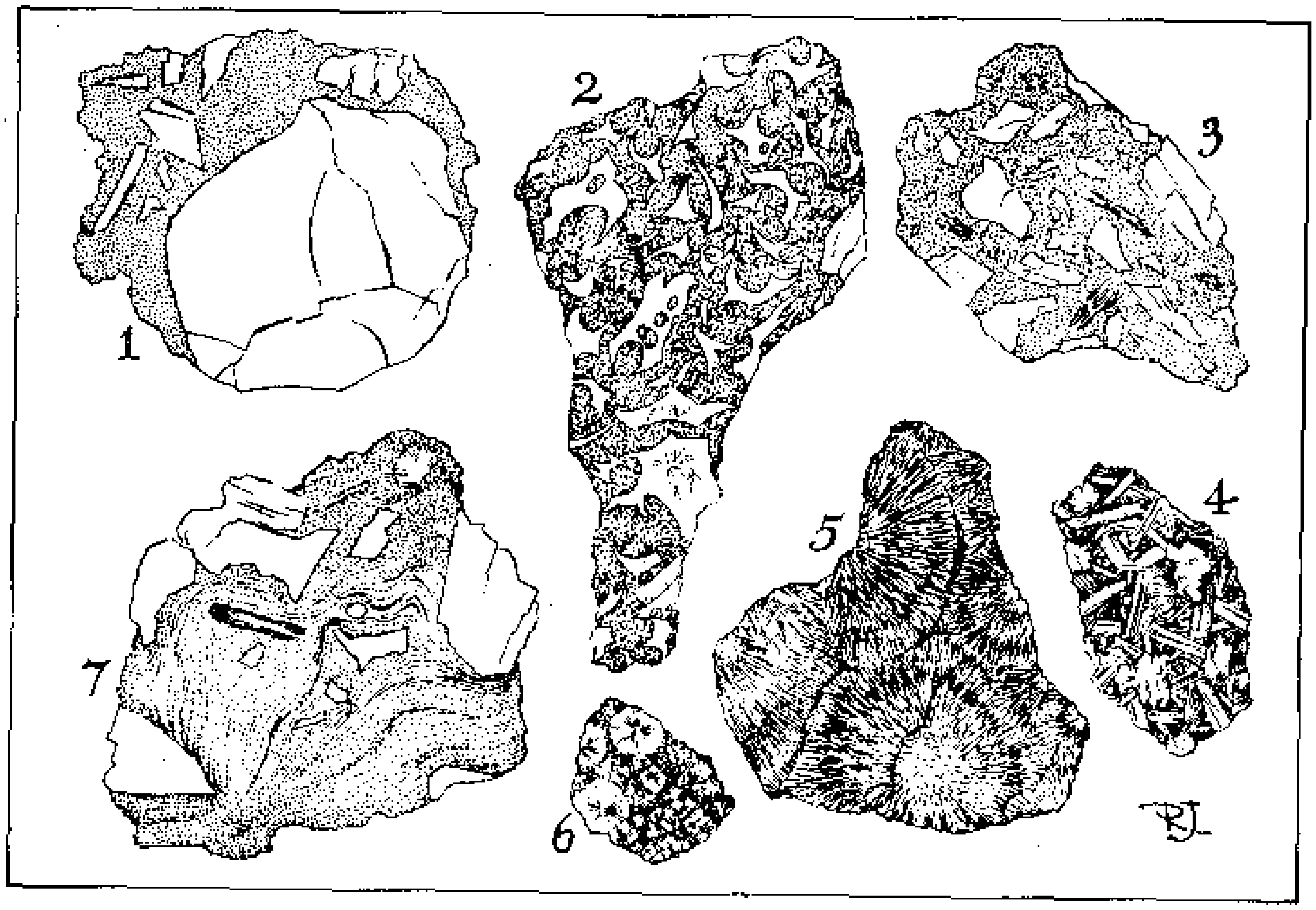

FIG. 4.—*Some typical, sand-sized, volcanic rock fragments: 1) and 3) coarse and fine* grained vitric tuffs; 2) shards in a glassy matrix; 4) tightly interlocking mosaic of feldspar laths and quartz; 5) and 6) divitrified glass with spherulites; and 7) quartz and feldspar in a glassy matrix with strong flow structure.

diffraction techniques. The dominant minerals, in relative order of abundance, are quartz, feldspar, montmorillonite and zeolite. The latter two minerals account for less than 5 percent of the total while quartz and feldspar are present in about equal amounts. Table 6 documents the chemical composition of the clay and silt fraction, which has much less SiO_2 and more FeO and CaO than the chemical analyses of the sands.

CHEMICAL COMPOSITION.—Four bulk sand samples were chemically analized by the Geochemistry Section of the Indiana Geological Survey. Major and minor element determinations were made by wet chemical methods and x-ray emission spectrography. Trace elements were analyzed by optical emission spectrography. The boron percentage of less than 2 micron clay content determinations for samples Nos. 1, 5, and 11 were performed by the Illinois Geological Survey.

The uniformly high silica and aluminum content plus abundant iron, magnesium, calcium, sodium and potassium clearly reflect the high proportion of unstable mineral and rock fragments contained within these sands (Table 3). It is noteworthy that, in spite of a considerable range in the proportion of the various mineral constituents, individual samples are quite similar in overall composition (Table 6).

TABLE 6.—Chemical composition of alluvial material

Oxides	Sand samples 1	2	3	5	Clay and silt
SiO_2	68.4	70.2	70.5	73.5	62.1
TiO_2	0.59	0.62	0.47	0.34	0.48
Al_2O_3	14.9	13.90	15.1	13.3	14.9
Fe_2O_3	2.83	2.63	1.92	1.55	0.43
FeO	0.84	0.91	0.56	0.56	2.28
MnO	0.07	0.06	0.05	0.04	0.10
MgO	0.89	0.92	0.36	0.55	1.34
CaO	1.71	1.69	1.60	1.13	2.15
Na_2O	2.80	2.30	2.72	2.34	1.55
K_2O	3.14	3.21	3.91	4.01	3.02
H_2O	3.11	2.67	2.16	1.80	4.65
P_2O_5	0.05	0.05	0.03	0.02	— —
CO_2	0.17	0.36	0.07	0.12	0.27
S	< 0.01	< 0.01	< 0.01	< 0.01	0.02
Loss on heating					12.6
Total:	99.51	99.13	99.69	99.32	100.95

PETROLOGIC AND CHEMICAL SIGNIFICANCE

Petrologically, the sands in our study area are easily classified. Rhyolitic rock fragments are three times more abundant than either quartz or feldspar, (Figure 5), clay is of minor abundance and the detritus is texturally immature (Table 3). Using the classification of Dott (1964, fig. 3), the sands in our study area are *medium grained, moderately sorted, angular, rhyolitic, lithic arenites*, the modifier rhyolitic being included to emphasize the great dominance of rhyolitic rock fragments.

Chemical analyses confirm the freshness of the detritus as seen under the microscope. Table 7 compares our average analyses with that of the average rhyolite. With but few exceptions the two compare closely thus fully justifying using "rhyolitic" as an adjectival modifier. Good comparison implies that in the semi-arid mountainous terrain of the Sierra Madre, chemical weathering has had but little impact on the chemical composition of the detritus eroded from it.

Also given in Table 7 are the average compositions of graywacke, arkose and orthoquartzite. Sierra Madre sands have more SiO_2 than a graywacke,

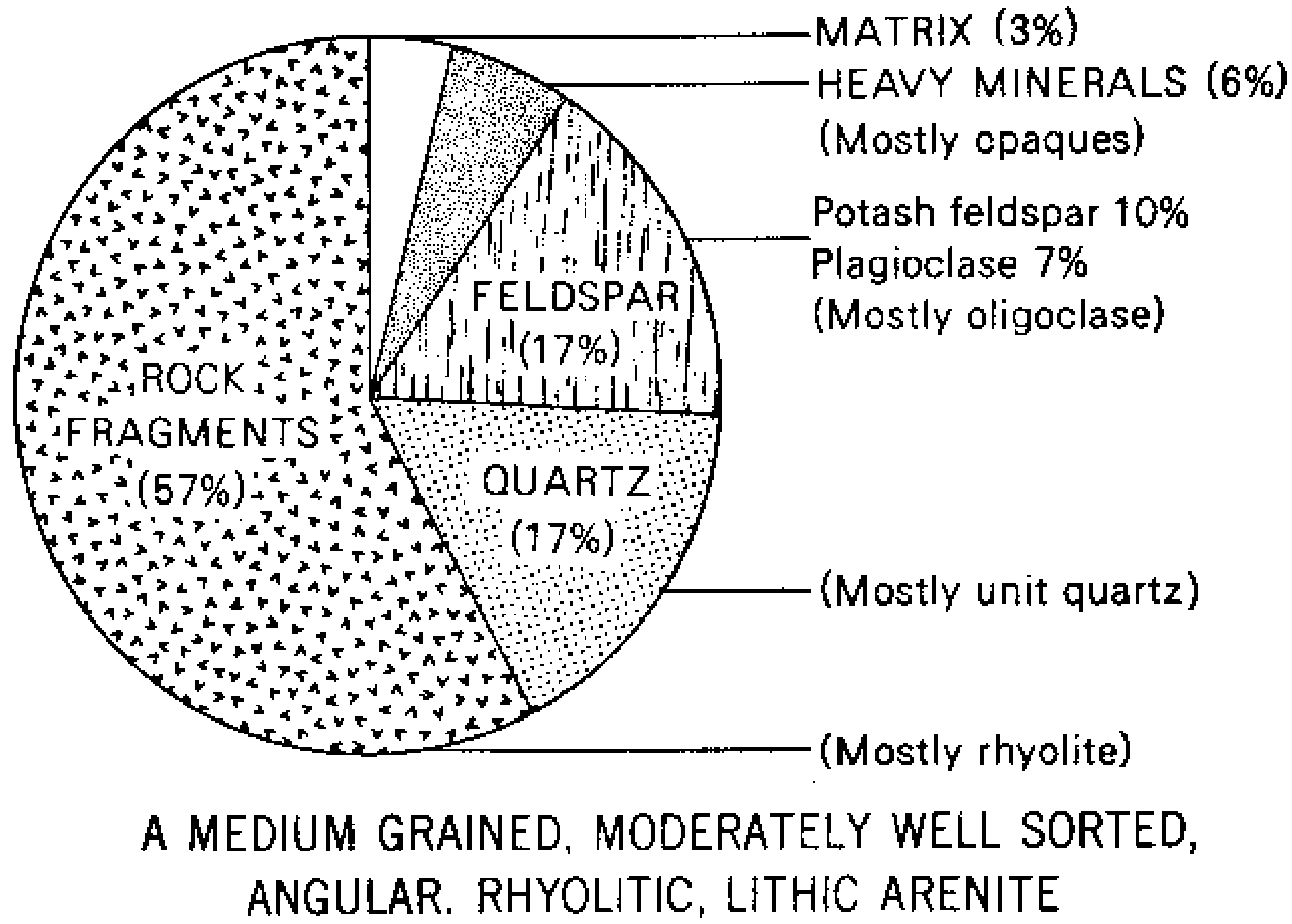

Fig. 5.—Sierra Madre sands.

slightly more AL_2O_3 than the graywackes and are richer in Fe_2O_3; the latter resulting from the abundance of magnetite in the fine fraction. But because of its reducing environment, graywacke has appreciably more FeO.

Another comparison of interest is the Na_2O/K_2O ratio and its relation to SiO_2 content in sandstones as well as in the igneous rocks (Figure 6). In igneous rocks there is a clear trend of decreasing Na_2O/K_2O ratio with decreasing SiO_2. Sierra Madre sands have a ratio close to that of the average rhyolite and alkali granite. Like arkoses and orthoquartzites, Na_2O/K_2O ratio of Sierra Madre sands is much smaller than that of the average graywacke.

Boron content of the muds in Sierra Madre streams was also investigated to further test its value as a discriminator between marine and freshwater muds (Shaw and Bugry, 1966). Shimp *et al.* (1969) found that this discrimination is heightened if the amount of less than 2 micron clay was also determined. Using only modern muds, they obtained the following discriminant function (p. 7) for the boron-clay pair as an environmental discriminator between marine and fresh water environments.

$$Z = 0.00095X_{Boron} - 0.07910X_{Clay}$$

Boron-clay content for three mud samples is: 32, 28.2; 14, 19.2; 25, 32.5, the boron being measured in parts per million and the less than 2 micron

TABLE 7.—Some average chemical compositions.

Oxides	*Sierra* Madre Sands	Rhyolite[1]	Gray Wacke[2]	Arkose[2]	*Quartzite*[2] Ortho
S_iO_2	70.7	73.66	66.7	77.1	95.4
TiO_2	0.49	0.22	0.6	0.3	0.2
Al_2O_3	14.30	13.46	13.5	8.7	1.1
FeO	0.71	0.75	3.5	0.7	0.2
Fe_2O_3	2.25	1.25	1.6	1.5	0.4
MnO	0.05	0.03	0.1	0.2	—
MgO	0.67	0.32	2.1	0.5	0.1
CaO	1.54	1.13	2.5	2.7	1.6
Na_2O	2.54	2.99	2.9	1.5	0.1
K_2O	3.56	5.33	2.0	2.8	0.2
H_2O+	2.43	—	2.4	0.9	0.3
H_2O-		—	0.6	—	—
P_2O_5	0.03	—	0.2	0.1	—
CO_2	0.18	—	1.2	3.0	1.0
S	0.002	—	—	—	—
Total	99.2	99.1	100.1	100.0	100.7
Na/K	0.7	0.6	1.3	0.5	0.5

1 After Nockolds Table 1, Page 1012.

2 After Pettijohn Table 12, Page S 15.

clay content expressed as percent. Substitution in the above discriminate function yields Z values of −2.20022, −1.50542 and −2.54700. The discriminating value of Z between the two environments is −1.94194 so that 2 of the samples would be correctly classified as of fresh water origin, as indeed they are, but the other (14, 19.2) assigned to a marine environment. Although but 14 ppm boron were present, its very low clay content (19.2%) causes it to be misassigned to the marine realm. This shows that clay content can be of critical importance when using boron determined from whole mud analyses to distinguish between marine and fresh water environments.

The generally low values of boron in these muds, all of which were ultimately derived from the weathering of rhyolitic tuff, suggest that a volcanic provenance may not always be an important factor responsible for high boron concentrations (*cf.* Levinson and Ludwick 1966, p. 857).

Figure 7 shows a comparison of Sierra Madre sands with those of 18 other representative volcaniclastic sands of erosional origin from the circum-

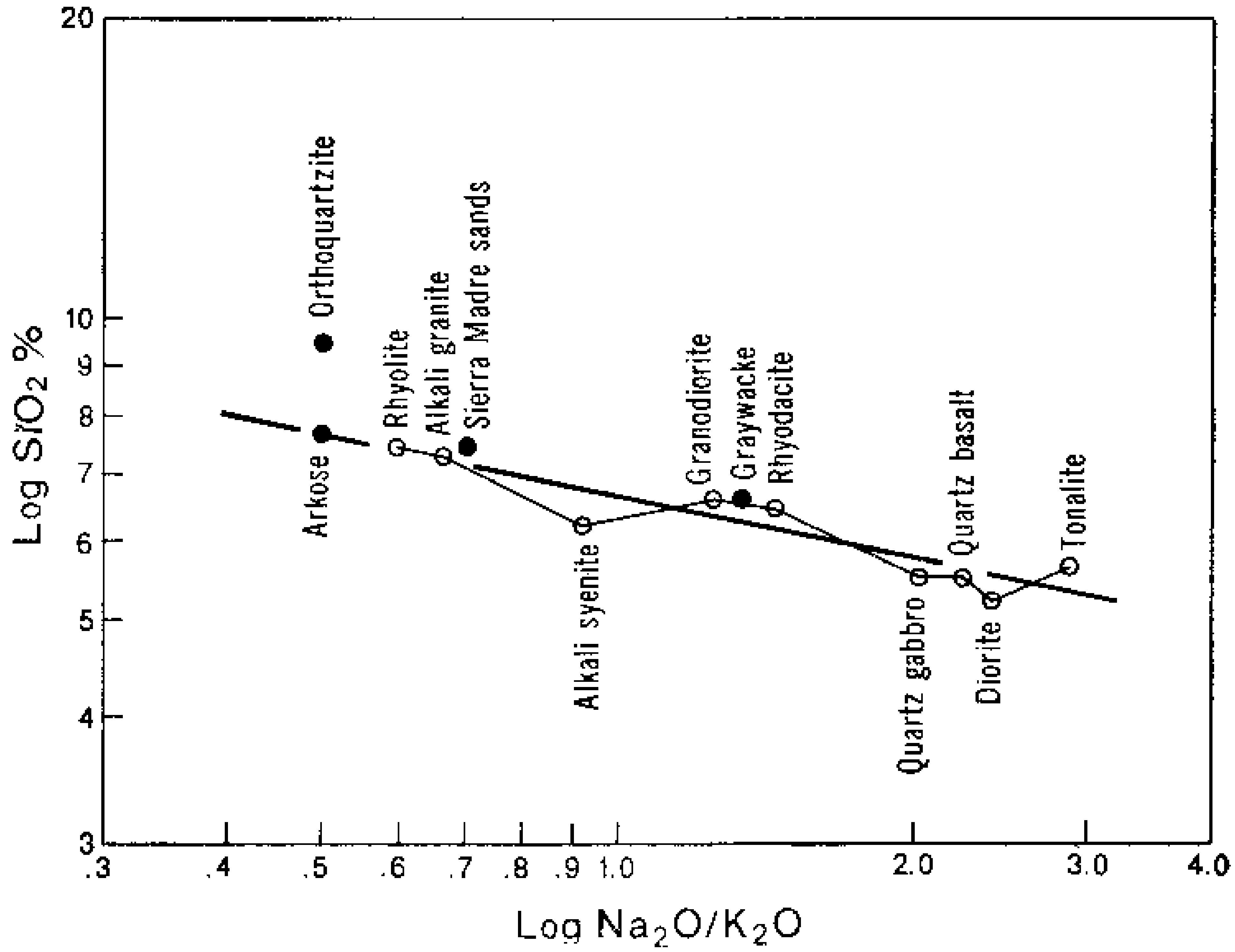

FIG. 6.—SiO_2 *versus* K_2O/Na_2O for igneous and sedimentary rocks

pacific region. Ages from lower Carboniferous to Recent are included. What conclusions follow from this plot? Perhaps most striking is the dominance of rock fragments over feldspar (13 to 6). Perhaps no other petrographic type is as rich in rock fragments as the volcaniclastic sands. Two sands, one of Triassic-Permian age from the Sidney Basin in Australia and the other a recent sand from Viti Levu, Fiji, have ratios of more than 85 percent! Another striking feature of the circumpacific volcaniclastics in their deficiency in quartz. Sierra Madre sands stand apart from most in this respect, however, even though they have a first cycle origin, because rhyolite rather than andesite or more basic volcanics was their source rock. *Wackes* rather than arenites predominate in the circumpacific suite. Doubtlessly, much of this is due to the secondary alteration of the fine grained volcanic rock fragments which, through squeezing and diagenesis, can become indistinguishable from "detrital" matrix.

How will petrographic composition of Sierra Madre sands change as they are progressively recycled? Rock fragments will be eliminated both chemically and mechanically more rapidly than feldspar so that quartz-

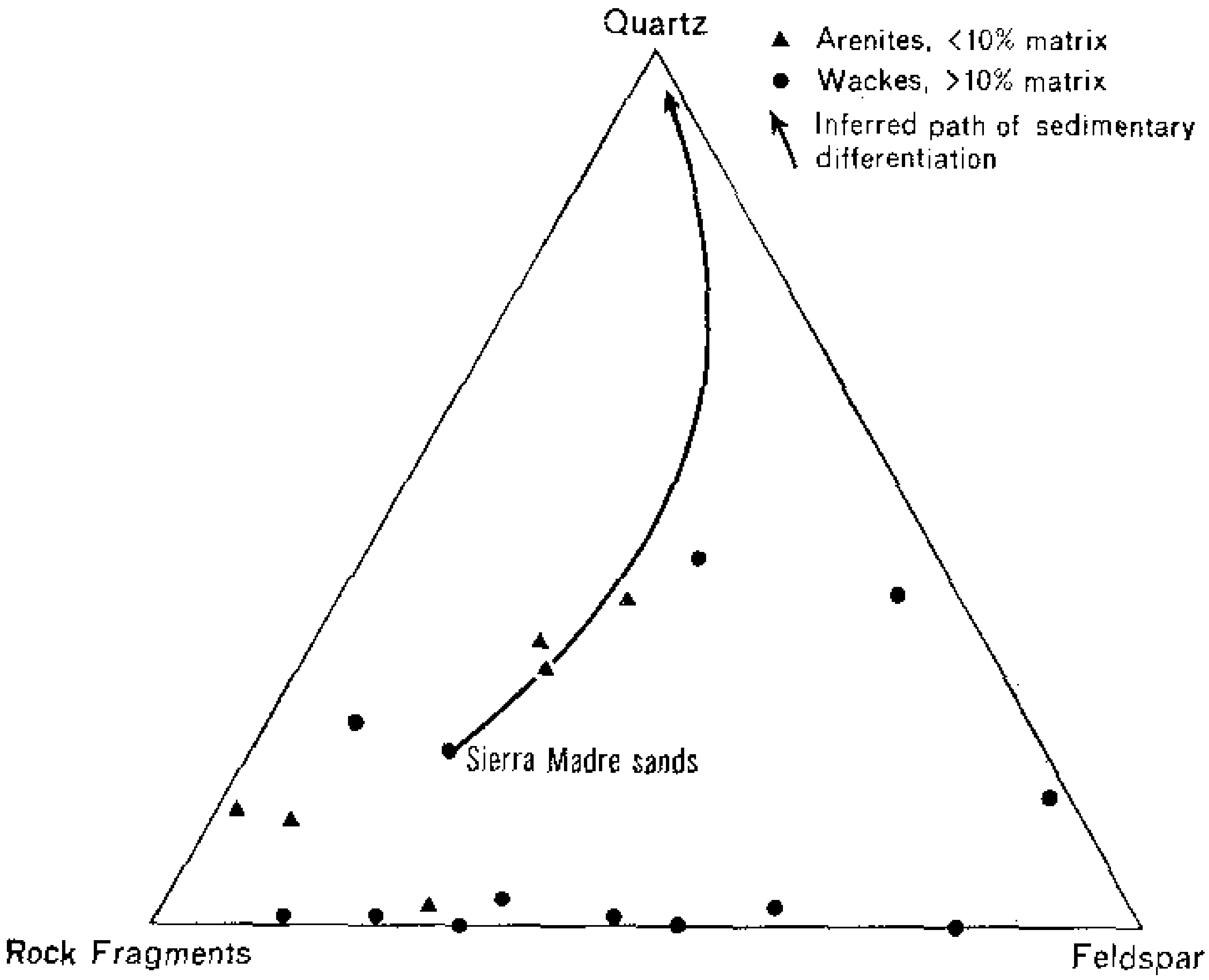

FIG. 7.—Feldspar-quartz-rock fragment composition of volcaniclastic sands and sandstones of circumpacific region

feldspar-rock fragment proportions will follow the path shown in Figure 7. Intense chemical weathering could hasten this progress. Strong mechanical abrasion and sorting such as could occur along a coast line with high wave energy would have a similar effect. Unfortunately, intense abrasion would remove embayments and glassy material so that specific evidence of the volcanic origin would be lost. Chemical weathering on the other hand, would leave quartz embayments, euhedral outline, and fracturing plus the dominance of unit quartz as distinctive volcanic earmarks.

Considering for the moment that sedimentary differentiation could eventually concentrate Sierra Madre sand into an orthoquartzite, one is struck by the small amount of quartzose sand and the enormous amount of argillaceous material that would result. By volume the ratio would be some four units of argillaceous material per unit volume of quartz. Conceivably, the quartz-free volcaniclastic sands of andesitic and basaltic derivation would ultimately be reduced to argillaceous material so that its volcanic affinities would be erased—at least petrographically. Fortunately, sedimentary differentiation has not gone so far in many Mesozoic and Tertiary geosynclines so that careful attention by sedimentary petrologists to feldspar composition and index of refraction of glass, should it still remain, offer the best means of identifying the predominant volcanic rock type. General characteristics of volcanic debris include abundance of zoned plagioclase, shards and other glassy material, embayments of quartz and feldspar and, among the heavy minerals, oxy-hornblende.

In conclusion, we would like to comment on the philosophy of our study. As sedimentary petrologists primarily concerned with the clastic fill of ancient basins, we have been most aware of the shortcomings of inferences about the character of source regions based only on the petrology of the fill itself. One way to improve our understanding is to select a relatively few homogeneous terrains where rock type, climate and relief are known and determine the character of the resultant detritus. Perhaps as few as a dozen different end-member terrains, with duplicate or triplicate studies of each type, would go far to improve our understanding. Should this be done, sampling streams is much superior to sampling the soils of the source area for not only is the detritus already on its way toward a sedimentary basin, but even the smallest stream provides a much more homogeneous sample than a soil profile. Hence fewer samples need to be studied. We believe that a relatively modest investment of time and money studying the products of present-day erosion in selected, homogeneous terrains would do much to enhance our ability of interpreting the past.

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