INGERSOLL et al 1984

THE EFFECT OF GRAIN SIZE ON DETRITAL MODES: A TEST OF THE GAZZI-DICKINSON POINT-COUNTING METHOD[1]

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ABSTRACT: Differing methods of determining detrital modes of sand/sandstone have been developed by different "schools" due to different goals and different geologic settings. The Gazzi-Dickinson method of point counting was developed to maximize source-rock data, while minimizing the time, effort, and expense of gathering such data. Use of the method minimizes variation of composition with grain size, thus eliminating the need for sieving and multiple counts of different size fractions. Unsorted samples of any sand size may be used, thus allowing direct comparison between modern sands and poorly sorted ancient sandstones. The application of actualistic petrologic models relating composition to tectonic setting thus is facilitated.

The unique aspect of the Gazzi-Dickinson method of point counting is the assignment of sand-sized crystals and grains within larger fragments to the category of the crystal or grain, rather than to the category of the larger fragment. In addition, every attempt is made to reconstruct original detrital compositions in spite of subsequent alterations.

Six unconsolidated Holocene sand samples derived from a variety of source rocks in north-central New Mexico were collected, sieved, impregnated, sectioned, stained and point-counted, using both traditional and Gazzi-Dickinson methods. Results of these counts provide a comparative test of traditional and Gazzi-Dickinson methods.

There are two reasons for variation of modal composition with grain size: 1) the breakage of fragments into constituent grains, and 2) actual mineralogic variation with grain size. The Gazzi-Dickinson method successfully eliminates the first source of compositional grain-size dependency. No point-counting method eliminates the second source. Use of the Gazzi-Dickinson method on unsorted samples produces results that are consistent with those from different size fractions of the same samples. Lithic-fragment compositions (for example, LmLvLs, QpLvmLsm) are especially consistent and provide the most useful parameters for relating composition to source rock and, ultimately, to tectonic setting.

INTRODUCTION

Compositions of detrital sediments are controlled by four factors: provenance, transportation, depositional environment, and diagenesis (Suttner 1974). An individual study of ancient sediments commonly has the goal of understanding one or more of these factors. Study of diagenesis commonly is most straightforward because it is the most recent process affecting a given sediment. On the other hand, reconstruction of provenance may be the most complicated because of subsequent modifications imposed by the other three factors. Reconstruction of provenance is most straightforward in situations where the other three factors have had minor effect. The provenance of a sediment includes all aspects of the source area, including source rocks, climate, and relief (Pettijohn et al. 1972). In areas of intense tectonic/magmatic activity, source-rock type determines sediment composition more than do climate and relief (Dickinson 1970). Where tectonism/magmatism is absent, climate and relief are more important in determining composition (Basu 1976). An additional complicating factor is that recycling of sediment may have a

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 54, NO. 1, MARCH, 1984, P. 0103–0116

profound effect on compositions but commonly may be difficult to recognize or quantify (Blatt 1967).

Different "schools" of sedimentary petrology have evolved over the last several years which are in apparent competition and disagreement concerning which factors are the most important in determining sediment (primarily sand/sandstone) compositions. These apparent conflicts result from contrast in emphasis. Petrologists interested in diagenesis employ different techniques than do those interested in paleoclimates or source rocks. Those working in tectonically active areas can determine source rocks more easily, whereas comparative paleoclimates can be determined more easily where source rocks are constant and tectonic activity is mild. None of these schools of sedimentary petrology is better than another; each has developed techniques to maximize the type of information most desired. The present paper is a discussion of the relative merits of a point-counting method developed independently by Gazzi (1966) (discussed by Gazzi et al. 1973; Zuffa 1980) and Dickinson (1970) that attempts to maximize information regarding source rocks in tectonically active settings. Petrologists interested in paleoclimates, transport history, diagenesis, or other aspects of sand/sandstone composition will probably choose alternative methods.

Far too few data exist relating compositions of Holocene sand to known source rocks, climates, and tectonic settings (Blatt 1967; Suttner 1974). Such data are needed in order to develop actualistic petrologic models which can be applied to the interpretation of ancient sandstones, whether for paleoclimate or paleotectonic studies. Use of such models will lessen the use of ad hoc hypotheses to explain sandstone compositions (Blatt 1967). The present study is the first step in a project designed to study Holocene sand from a variety of known source rocks in north-central New Mexico. Samples were collected from arroyos where less than 10 km of transport had occurred, so that breakdown of fragments due to stream transport has been negligible (see, for example, Basu 1976). The methods used are designed to maximize the type of information useful in determining source rocks and to minimize the time, effort and expense in gathering data.

GRAIN SIZE AND MODAL COMPOSITION

The apparent dependence of sandstone detrital modes on grain size has been demonstrated by several workers (see, for example, Basu 1976; Blatt 1967; Mack and Suttner 1977; Young et al. 1975). However, there are two basic schools of thought concerning the subject: 1) that which believes that there is a fundamental dependence of modal composition on grain size (Basu 1976; Mack and Suttner 1977; Suttner 1974); and 2) that which believes that modal composition can be determined independently of grain size (Dickinson 1970; Gazzi 1966).

The former school believes that grain-size change is accompanied by compositional variation as original clasts are altered in size and mineralogy through chemical and physical weathering processes (Basu 1976; Mack and Suttner 1977; Suttner 1974). Polymineralic, coarsely crystalline grains are counted as lithic fragments. Through mechanical breakdown, the proportion of coarse-grained lithic fragments decreases as the constituent minerals increase in the finer grain sizes. The traditional view is that this is an obvious compositional dependence on grain size. Additionally, composition is considered to be a complex function of provenance, transportation history, depositional modification, and diagenesis (Suttner 1974).

Less traditional methods (Dickinson 1970; Gazzi 1966; Gazzi et al. 1973; Graham et al. 1976; Ingersoll 1978; Ingersoll and Suczek 1979) place greater emphasis on using petrographic techniques to reconstruct original detrital compositions independent of grain size. Dickinson (1970) argues that the identification and recording of mineral crystals of sand size, whether within coarse-grained lithic fragments or not, reduces compositional dependence on grain size. Additionally, careful petrographic techniques (applied by both schools of methodologists) allow the reconstruction of grains severely altered because of physical or chemical diagenetic effects. Thus, alterations such as those described by Walker et al. (1978) do not change detrital modes significantly. The Gazzi-Dickinson method reduces the effects of grain size and alteration on composition and thereby allows accurate determination of original detrital mode and provenance.

TABLE 1.—*Grain parameters (after Dickinson 1970; Graham et al. 1976; and Ingersoll and Suczek 1979)*

Counted parameters	Recalculated parameters
Qp = polycrystalline quartz (inc. chert)	Q = Qm + Qp
Qm = monocrystalline quartz	F = P + K
P = plagioclase feldspar	L = Lv + Lm + Ls + Lp
K = potassium feldspar	Lvm = Lv + xLm (where x ranges from 0 to 1 [operationally, usually 0])
Lv = volcanic-hypabyssal lithics	Lsm = Ls + (1 − x)Lm (operationally, Lsm usually equals Ls + Lm)
Lm = metamorphic lithics	Framework = Q + F + L + M + D + Misc.
Ls = sedimentary lithics	QFL%Q = 100Q/(Q + F + L)
Lp = plutonic lithics (traditional method only)	QFL%F = 100F/(Q + F + L)
M = phyllosilicates	QFL%L = 100L/(Q + F + L)
D = dense minerals	Framework%M = 100M/Framework
Misc. = miscellaneous and unidentified	Framework%D = 100D/Framework
(x = fraction of metavolcanics in Lm [noted separately])	LmLvLs%Lm = 100Lm/(L − Lp) LmLvLs%Lv = 100Lv/(L − Lp)
	LmLvLs%Ls = 100Ls/(L − Lp)
	QpLvmLsm%Qp = 100Qp/(L − Lp + Qp)
	QpLvmLsm%Lvm = 100Lvm/(L − Lp + Qp)
	QpLvmLsm%Lsm = 100Lsm/(L − Lp + Qp)

The purpose of this study is to demonstrate the usefulness of the Gazzi-Dickinson method in determining the provenance of Holocene sands derived from contrasting source areas under constant climatic conditions. Because Holocene sands are generally unconsolidated, it is possible to separate grain-size classes and then to perform detailed petrographic studies on each size fraction. This study is also designed to show that, in most cases, the time required for accurate source-rock determinations can be reduced by eliminating point counts of individual grain-size classes. Data based on unsorted Holocene sand samples can be applied directly to the study of ancient sandstones of any grain size and degree of sorting.

SAMPLE COLLECTION AND PREPARATION

Six unconsolidated sand samples with known (and in some cases, mixed) provenance were collected for this study from arroyos in north-central New Mexico. The sands collected were derived from a wide variety of source rocks: metamorphic, plutonic, basaltic to felsic volcanic, and sedimentary. The samples were dried; disaggregated by hand, taking care not to break any grains; and split. One fraction of each split sample (Fraction 1) was saved as an unsieved representative. The remaining fraction was sieved at 1 ϕ intervals, resulting in five fractions. Fractions 2, 3, 4, 5, and 6 represent the intervals 4–3 ϕ, 3–2 ϕ, 2–1 ϕ, 1–0 ϕ, and 0–(−1) ϕ, respectively. The six fractions were poured into molds and impregnated with epoxy. The resulting artificial rocks were cut into standard thin sections and stained for plagioclase and potassium feldspars.

POINT-COUNTING METHODS

Each operator studied all six thin sections made from each sample. Parameters counted are described in Table 1; these parameters and criteria for their identification are described by Dickinson (1970), Graham et al. (1976), Ingersoll (1978), and Ingersoll and Suczek (1979). Matrix and cement were not counted (the unconsolidated sands contain little of either); grains finer than .03 mm (matrix) that remained in sieved fractions due to insufficient sieving were ignored in the counts. A few coarse silt grains (between .03 and .0625 mm) were counted in some sections.

For each thin section, each operator counted 300 points, using the maximum grid spacing that resulted in coverage of the entire slide. Because the sands are fresh and unaltered, identification of each grain was accomplished with certainty for almost all grains; therefore, 300 counts per section yielded statistically reliable values for all parameters (see, for example, Van der Plas and Tobi 1965). In other words, operator error does not contribute significantly to the variability of the results (see, for example, Ingersoll 1978). Some operators chose to make separate counts of each section (once using the traditional method and once using the Gazzi-Dickinson method), whereas other operators chose to use both counting methods simultaneously.

The primary way in which the Gazzi-Dickinson method differs from the traditional method is that monomineralic crystals and other grains of sand size (> .0625 mm) that occur within larger rock fragments are classified in the category of the crystal or other grain, rather than in the category of the larger rock fragment. Thus, plutonic rock fragments are counted as quartz, feldspar, mica, or whatever else is intersected by the cross hair. Other rock fragments containing sand-sized crystals in a fine-grained groundmass are counted as those crystals or as L, as determined by which part of the fragment is intersected. More rarely, a volcanic rock fragment of sand size within a larger sedimentary rock fragment would be classified as Lv rather than as Ls (see Table 1). There are two reasons for using this approach: 1) modal composition does not change due to simple breakage of grains (for example, weathering of granite produces quartz, feldspar, micas, and miscellaneous minerals no matter what the grain size of the sediment); and 2) counting of poorly sorted or coarse-grained sand or sandstone is faster because the operator does not have to determine in what kind of grain a sand-sized crystal occurs. This allows point counts to be completed at high magnification without frequent shifting to lower magnification to determine coarse lithic types. Also, diagenetically altered and squashed sandstones (including "graywackes") are treated more efficiently because all monocrystalline grains are treated similarly whether they occur as discrete grains or as phenocrysts or microphanerites. Separate note may be made of the relative percentages of discrete grains versus phenocrysts or microphanerites if this information is deemed useful. (Rarely does this type of information provide source-rock data that are not already known from the standard counts using this method.)

Use of the Gazzi-Dickinson method results in higher percentages of Q, F, M, and D, and lower L values than does the traditional method when counting coarse samples. Fine-grained samples show similar values using both methods. Also, the Gazzi-Dickinson parameters do not include a category for plutonic lithic fragments because such grains are counted as their constituent crystals. A few microphaneritic igneous fragments are included in the Lv category (volcanic and hypabyssal) if the part of the fragment counted contains crystals finer than sand. Fine-grained polycrystalline, microcrystalline, and cryptocrystalline quartz may be combined with monocrystalline quartz to make QFL% Q or with unstable lithic fragments to make QmFLt% Lt (total lithics) (Graham et al. 1976). The former method is followed here.

Only virtually pure silica is classified as Qp using the Gazzi-Dickinson method. The slightest amount of impurities within a chert grain results in this grain being classified as Ls; a single feldspar microcryst within a siliceous volcanic fragment makes it Lv; and a single flake of primary mica within a polycrystalline-quartz grain makes it Lm. This method differs from that of the Indiana "school" (for example, Basu 1976; Mack 1981; Mack and Suttner 1977; Suttner 1974; Suttner et al. 1981; Young et al. 1975); these workers use a ten-percent cutoff rather than a zero-percent cutoff. Using a ten-percent cutoff has the desirable effect of lessening variation of composition due to the presence of minor components. However, it has the undesirable effect of classifying individual crystals differently in different occurrences. For instance, using the Indiana method, a coarse-grained metamorphic fragment consisting of 91% monocrystalline quartz and 9% monocrystalline mica is classified as Qm no matter what part of the fragment is counted (G. H. Mack, personal communication, 1982). However, upon breakage of the quartz grain in half, the modal composition of the resulting fragments would become 50% Qm and 50% Lm (Lm would seemingly appear from nowhere). Using the Gazzi-Dickinson method, 91% of the time that the unbroken fragment is counted, it would be classified as Qm and 9% of the time, as Lm. Upon breakage

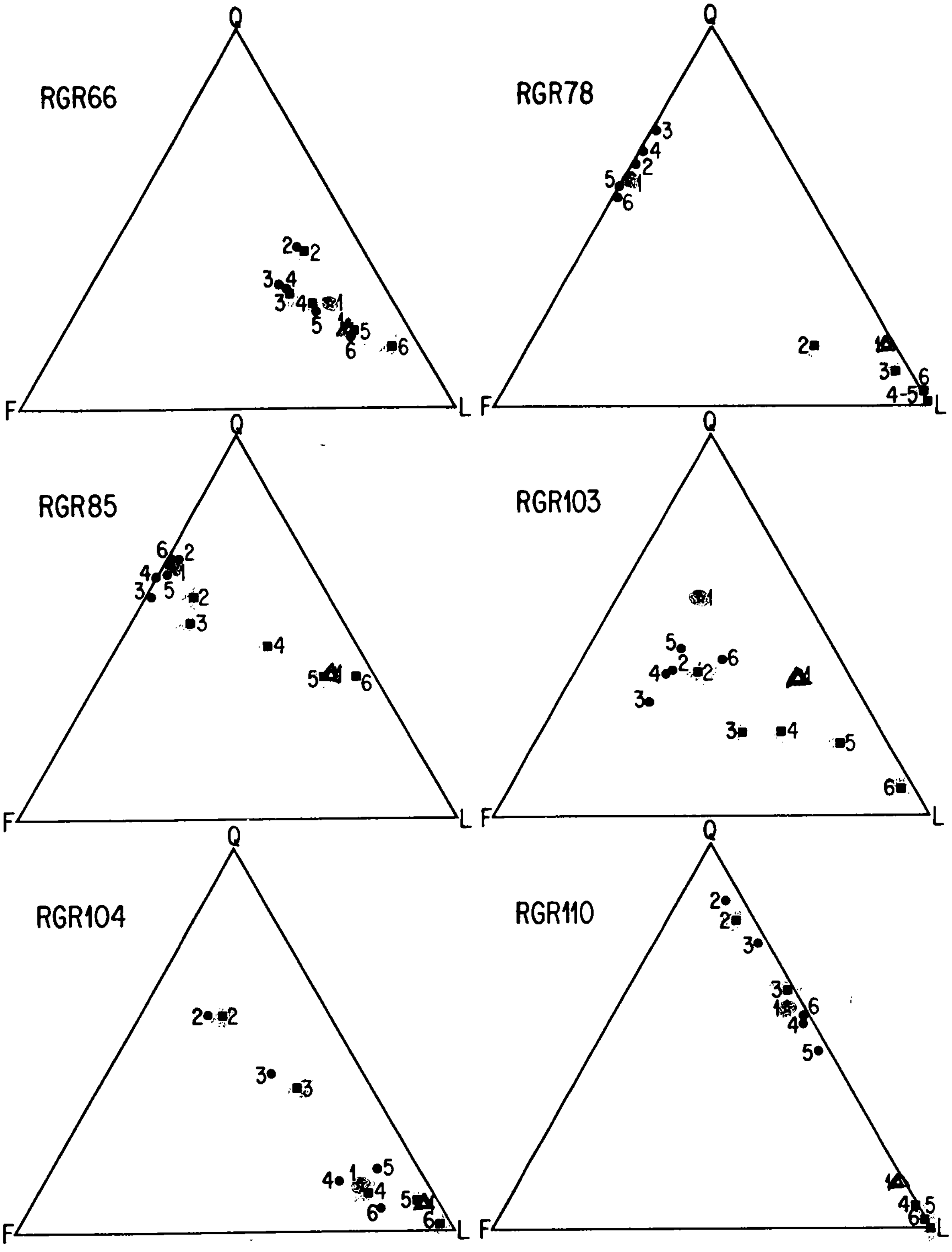

FIG. 1.—QFL triangles (see Table 1) for all 6 samples using both counting methods. Circles represent samples 2–6 (4–3 ϕ, 3–2 ϕ, 2–1 ϕ, 1–0 ϕ and 0–(–1) ϕ, respectively) using the Gazzi-Dickinson method; star represents Sample 1 (unsorted) using the Gazzi-Dickinson method. Squares represent Samples 2–6 using the traditional method; triangle represents Sample 1 using the traditional method. Same symbols are used in Figures 2–6. Samples RGR66 and RGR104 exhibit significant compositional variation with grain size no matter which counting method is used,

TABLE 2.—*Point-count data for unsieved fractions*

Sample	RGR66-1		RGR78-1		RGR85-1		RGR103-1		RGR104-1		RGR110-1	
Provenance	Felsic volcanics		Coarse schist		Mixed metamorphic		Mixed		Basalt and Sediments		Sediments	
Counting method	Gazzi-Dickinson	Traditional	Gazzi-Dickinson	Traditional	Gazzi-Dickinson	Traditional	Gazzi-Dickinson	Traditional	Gazzi-Dickinson	Traditional	Gazzi-Dickinson	Traditional
Qp	6	2	0	0	5	76	5	75	0	0	8	2
Qm	74	58	153	42	188	33	154	31	35	22	159	34
P	33	25	73	6	59	15	39	22	36	6	12	2
K	11	17	27	0	40	15	30	12	8	3	0	0
Lv	135	149	0	0	0	0	25	22	71	105	0	0
Lm	1	3	2	4	5	8	9	34	2	4	1	1
Ls	32	44	0	0	0	0	19	20	140	149	114	260
Lp	—	0	—	228	—	150	—	76	—	9	—	0
M	1	0	39	20	1	2	3	2	0	0	2	1
D	7	2	1	0	1	1	14	4	7	1	4	0
Misc.	0	0	5	0	1	0	2	2	1	1	0	0
Total	300	300	300	300	300	300	300	300	300	300	300	300

of the quartz grain in half, the composition would remain 91% Qm and 9% Lm. Thus, in the example given, use of the Indiana method results in the apparent formation of Lm from the breakage of Qm. This result would be difficult to explain from natural causes! Rather, it results from the counting method itself. In the above case, the Gazzi-Dickinson method produces more uniform, understandable results.

The above discussion illustrates that our "traditional" method is not identical to the Indiana method because we employed a zero-percent cutoff in all our counts. Nonetheless, results using our "traditional" method are likely to be far more similar to results acquired using the Indiana method than to those acquired using the Gazzi-Dickinson method.

RESULTS

Point-count data for the unsieved fractions of each of the six samples are shown in Table 2. This table illustrates the type of data collected and calculated for each size fraction of each sample. Data for both counting methods are given for each sample. The calculated QFL, LmLvLs, and QpLvmLsm percentages for all size fractions of each sample are listed in Table 3. Again, the data obtained using both counting methods are given for each sample.

Figure 1 shows QFL plots for each size fraction of each of the six samples using both methods. (The Indiana "school" uses the QFR notation. For clarity, it is recommended that future work using traditional methods be reported in the QFR notation, and that the QFL notation be used with the Gazzi-Dickinson method.) For Samples (RGR) 78, 85, 103 and 110, the points for each size fraction using the Gazzi-Dickinson method are more clustered than those using the traditional method. Samples 66 and 104 show scattering of points with both methods.

Figure 2 shows QpLvmLsm plots (Graham et al. 1976; Ingersoll and Suczek 1979) for Samples 66, 103, 104, and 110. Samples 78 and 85 are not shown because each has so few lithic fragments that this plot is statistically insignificant (Table 2). The triangular plots of Figure 2 show less variation with grain size than shown in Figure 1. Also, the points tend to cluster on these triangles using either counting method.

Figure 3 shows the variation in QFL% Q, F, and L versus grain size for Samples 85 and 104. For Sample 85, the Gazzi-Dickinson

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whereas the other four samples show significantly less compositional variation with grain size using the Gazzi-Dickinson method than using the traditional method. Notice tendency for unsorted samples (1) to have values near the averages of the other five samples, but generally closer to the coarser samples (4, 5, and 6) for either counting method (with the exception of Sample RGR103).

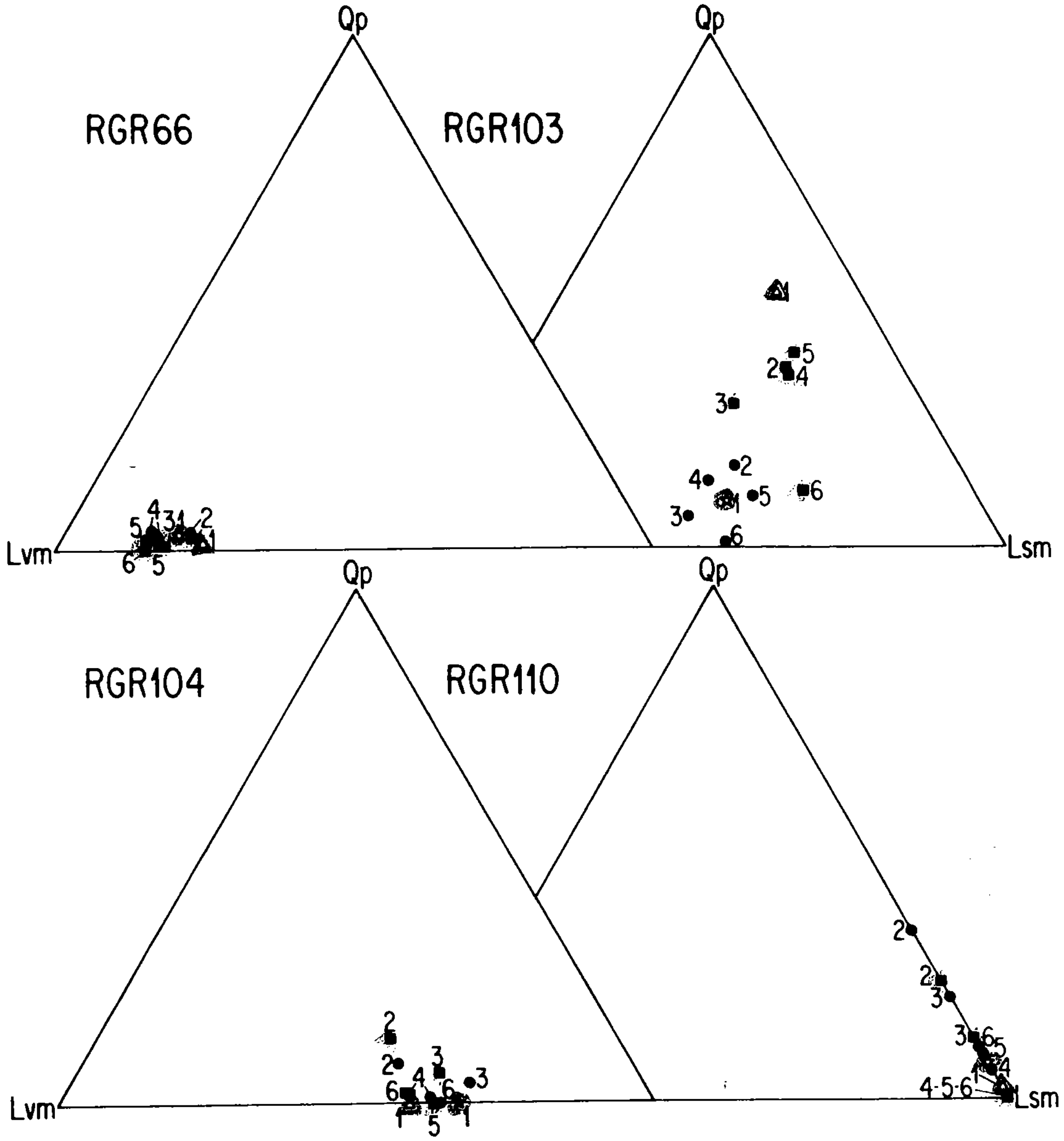

FIG. 2.—QpLvmLsm triangles (see Table 1) for four samples using both counting methods (Samples RGR78 and RGR85 have too few lithic fragments to be statistically significant). See Figure 1 for explanation of symbols. There is little compositional variation with grain size using either counting method, although Sample RGR103 shows considerable variation using the traditional method. The generally small amount of compositional variation indicates that this plot is a reliable indicator of provenance.

method shows much less variation due to grain size than the traditional method. Sample 104 shows considerable variation with grain size for both counting methods, although somewhat less using the Gazzi-Dickinson method, unless Fractions 2 and 3 (fine-grained) are not considered.

Figure 4 contains plots of LmLvLs and QpLvmLsm percentages versus grain size for two samples. Sample 103 shows considerable variation in LmLvLs percentages using either method; however, the Gazzi-Dickinson method systematically shows less variation with grain size. Both methods result in little

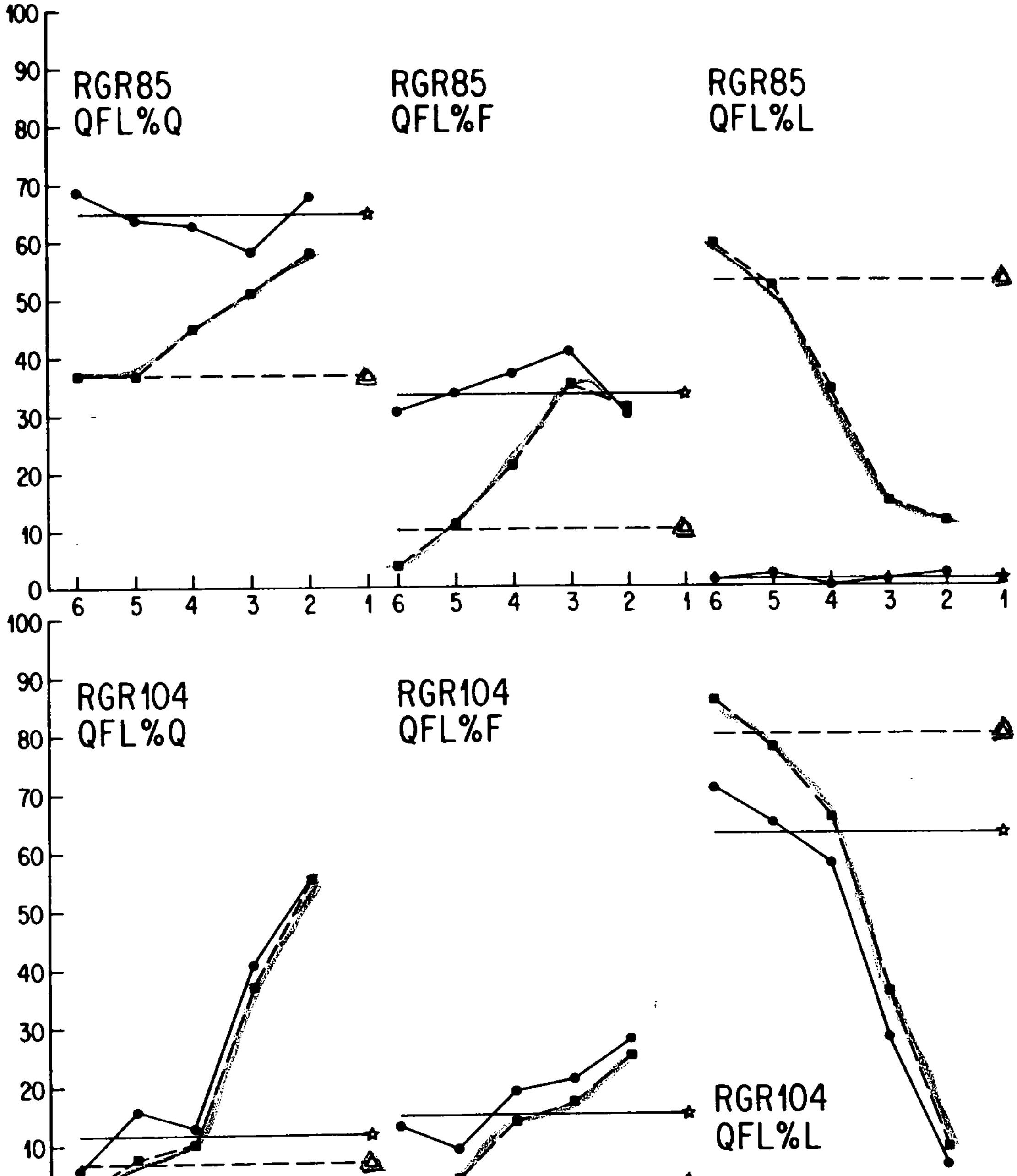

FIG. 3.—Binary plots of QFL% Q, F, and L versus grain size (coarser on left, finer on right, with Sample 1 being unsorted) for Samples RGR85 and RGR104. See Figure 1 for explanation of symbols. Solid lines connect results using Gazzi-Dickinson method; dashed lines connect results using the traditional method. Horizontal lines to left of unsorted samples (1) illustrate the degree to which these samples represent mean values. Total amount of compositional variation with grain size is less and the degree to which the unsorted sample represents the mean is greater using the Gazzi-Dickinson method than using the traditional method. Total amount of compositional variation is reduced considerably if the two finest fractions (2 and 3) are ignored.

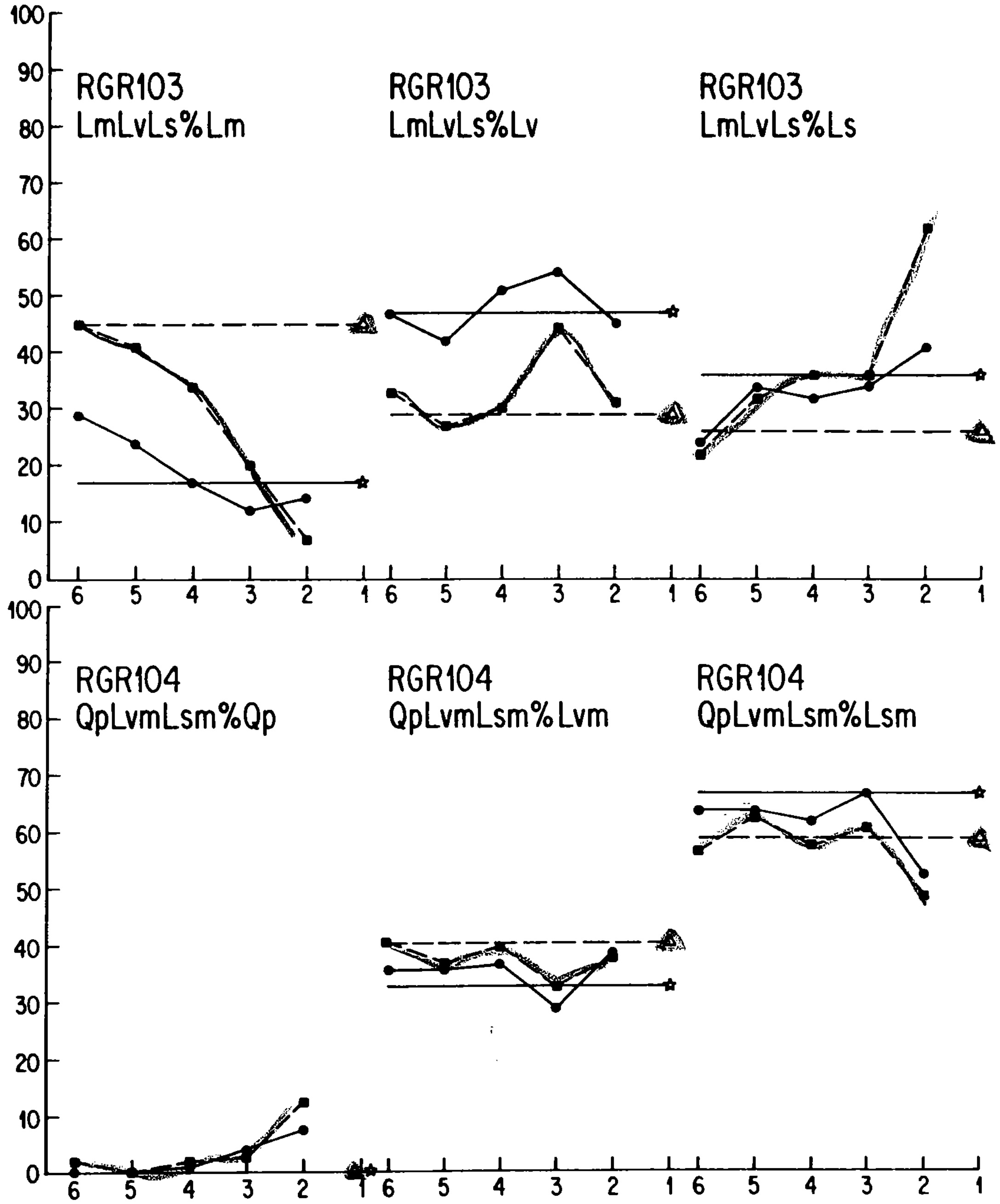

FIG. 4.—Binary plots of LmLvLs% Lm, Lv, and Ls (RGR103) and QpLvmLsm% Qp, Lvm, and Lsm (RGR104) versus grain size. See Figures 1 and 3 for explanation of symbols. Sample RGR103 shows significantly less compositional variation with grain size using the Gazzi-Dickinson method, whereas Sample RGR104 shows approximately the same degree of compositional variation with grain size regardless of counting method, but total amount of variation is small.

variation with grain size for QpLvmLsm percentages, as illustrated by Sample 104.

Examples of variations in parameter ratios with grain size, such as Qp/Q, Lv/L, and P/F, are shown in Figure 5. Again, the Gazzi-Dickinson method generally results in less variation than does the traditional method.

Figure 6 shows the variation in framework-

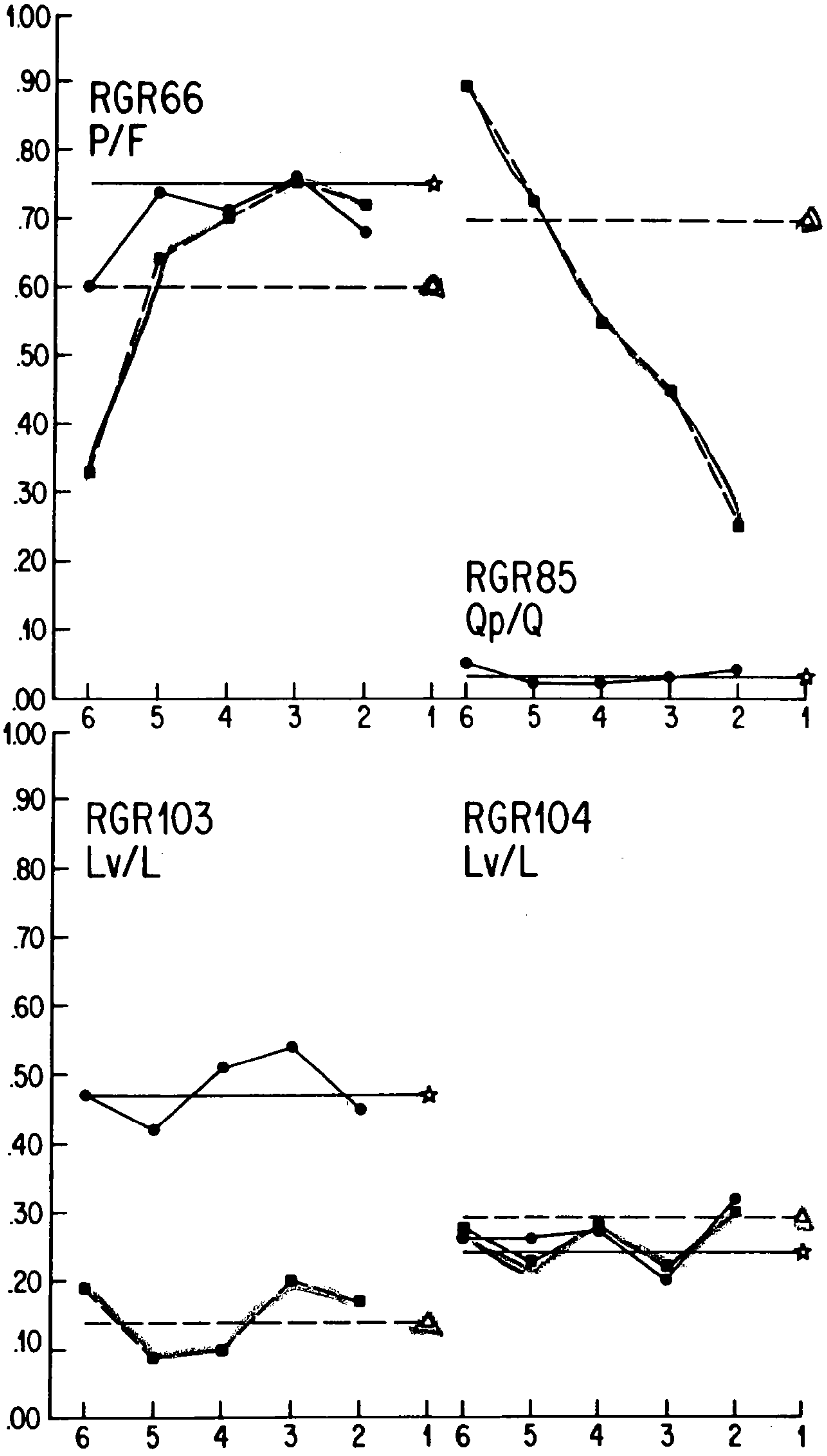

FIG. 5.—Binary plots of parameter ratios versus grain size. See Figures 1 and 3 for explanation of symbols. In most cases, the amount of compositional variation with grain size is either similar or less using the Gazzi-Dickinson method as compared to the traditional method.

TABLE 3.—*Recalculated Ternary percentages*

Sample (counting method)	QFL% Q	QFL% F	QFL% L	LmLv-Ls% Lm	LmLv-Ls% Lv	LmLv-Ls% Ls	QpLvm-Lsm% Qp	QpLvm-Lsm% Lvm	QpLvm-Lsm% Lsm
RGR66-1 (G-D)	27	15	58	1	80	19	3	78	19
RGR66-2 (G-D)	42	15	43	1	79	20	3	76	21
RGR66-3 (G-D)	32	24	44	1	84	15	2	82	16
RGR66-4 (G-D)	31	23	46	1	85	14	4	82	14
RGR66-5 (G-D)	25	19	56	0	86	14	2	84	14
RGR66-6 (G-D)	19	14	67	1	85	14	1	84	15
RGR66-1 (traditional)	20	14	66	2	76	22	1	75	24
RGR66-2 (traditional)	41	14	45	1	78	21	3	76	21
RGR66-3 (traditional)	30	23	47	1	82	17	1	81	18
RGR66-4 (traditional)	27	19	54	1	84	15	2	82	16
RGR66-5 (traditional)	20	13	67	0	83	17	1	82	17
RGR66-6 (traditional)	16	6	78	1	85	14	0	85	15
RGR78-1 (G-D)	60	39	1	100	0	0	0	0	100
RGR78-2 (G-D)	64	35	1	67	33	0	0	33	67
RGR78-3 (G-D)	73	26	1	50	0	50	0	0	100
RGR78-4 (G-D)	67	32	1	100	0	0	0	0	100
RGR78-5 (G-D)	58	42	0	—	—	—	—	—	—
RGR78-6 (G-D)	55	44	1	0	100	0	0	100	0
RGR78-1 (traditional)	15	2	83	100	0	0	0	0	100
RGR78-2 (traditional)	15	19	66	100	0	0	0	0	100
RGR78-3 (traditional)	8	4	88	67	0	33	0	0	100
RGR78-4 (traditional)	1	0	99	100	0	0	0	0	100
RGR78-5 (traditional)	1	0	99	100	0	0	0	0	100
RGR78-6 (traditional)	3	0	97	100	0	0	0	0	100
RGR85-1 (G-D)	65	33	2	100	0	0	50	0	50
RGR85-2 (G-D)	68	30	2	100	0	0	62	0	38
RGR85-3 (G-D)	58	41	1	100	0	0	71	0	29
RGR85-4 (G-D)	63	37	0	100	0	0	75	0	25
RGR85-5 (G-D)	64	34	2	100	0	0	36	0	64
RGR85-6 (G-D)	68	31	1	100	0	0	71	0	29
RGR85-1 (traditional)	37	10	53	100	0	0	91	0	9
RGR85-2 (traditional)	58	31	11	100	0	0	86	0	14
RGR85-3 (traditional)	51	35	14	100	0	0	96	0	4
RGR85-4 (traditional)	45	21	34	100	0	0	93	0	7
RGR85-5 (traditional)	37	11	52	100	0	0	84	0	16
RGR85-6 (traditional)	37	4	59	100	0	0	77	0	23
RGR103-1 (G-D)	57	24	19	17	47	36	9	43	48
RGR103-2 (G-D)	38	40	22	14	45	41	16	38	46
RGR103-3 (G-D)	30	49	21	12	54	34	6	51	43
RGR103-4 (G-D)	37	42	21	17	51	32	13	44	43
RGR103-5 (G-D)	44	35	21	24	42	34	10	38	52
RGR103-6 (G-D)	41	27	32	29	47	24	1	47	52
RGR103-1 (traditional)	36	12	52	45	29	26	50	14	36
RGR103-2 (traditional)	38	34	28	7	31	62	35	20	45
RGR103-3 (traditional)	22	32	46	20	44	36	28	32	40
RGR103-4 (traditional)	22	23	55	34	30	36	34	20	46
RGR103-5 (traditional)	19	11	70	41	27	32	38	17	45
RGR103-6 (traditional	7	3	90	45	33	22	11	29	60
RGR104-1 (G-D)	12	15	73	1	33	66	0	33	67
RGR104-2 (G-D)	56	28	16	2	42	56	8	39	53
RGR104-3 (G-D)	41	21	38	0	30	70	4	29	67
RGR104-4 (G-D)	13	19	68	0	37	63	1	37	62
RGR104-5 (G-D)	16	9	75	0	36	64	0	36	64
RGR104-6 (G-D)	6	13	81	0	36	64	0	36	64
RGR104-1 (traditional)	7	3	90	1	41	58	0	41	59
RGR104-2 (traditional)	56	25	19	4	44	52	13	38	49
RGR104-3 (traditional)	37	17	46	1	35	64	6	33	61
RGR104-4 (traditional)	10	14	76	0	41	59	2	40	58
RGR104-5 (traditional)	8	4	88	0	37	63	0	37	63
RGR104-6 (traditional)	2	2	96	0	42	58	2	41	57

TABLE 3.—*Continued*

Sample (counting method)	QFL% Q	QFL% F	QFL% L	LmLv-Ls% Lm	LmLv-Ls% Lv	LmLv-Ls% Ls	QpLvm-Lsm% Qp	QpLvm-Lsm% Lvm	QpLvm-Lsm% Lsm
RGR110-1 (G-D)	57	4	39	1	0	99	7	0	93
RGR110-2 (G-D)	85	4	11	0	0	100	33	0	67
RGR110-3 (G-D)	74	2	24	0	0	100	20	0	80
RGR110-4 (G-D)	53	2	45	0	0	100	6	0	94
RGR110-5 (G-D)	46	2	52	0	0	100	9	0	91
RGR110-6 (G-D)	55	1	44	0	0	100	10	0	90
RGR110-1 (traditional)	12	1	87	0	0	100	1	0	99
RGR110-2 (traditional)	80	4	16	0	0	100	23	0	77
RGR110-3 (traditional)	62	1	37	0	0	100	12	0	88
RGR110-4 (traditional)	6	0	94	0	0	100	0	0	100
RGR110-5 (traditional)	2	0	98	0	0	100	0	0	100
RGR110-6 (traditional)	0	0	100	0	0	100	0	0	100

percent phyllosilicates and framework-percent dense minerals with grain size. The two counting methods result in significant differences in these two percentages for some samples.

DISCUSSION

Point-counting methods are employed primarily to determine statistical representations of the modal compositions of rock samples. Variation of modal composition with changing grain size is due to 1) the breakage of grains during erosion, transport, and in situ weathering, and 2) actual mineralogic change with grain size. The latter may be caused by multiple lithologic sources contributing compositionally and texturally distinct grain sizes, and/or hydraulic or aerodynamic sorting of grains of variable density and/or shape.

Results using the Gazzi-Dickinson method are not affected significantly by the breakage of grains, but are affected by the segregation of minerals (see, for example, Fig. 1; Sample 104). Results using the traditional method are affected by both factors, as indicated by the large variation of composition with different grain size (Fig. 1) for all samples. Using the traditional method, there are fewer lithic fragments as grain size decreases (Fig. 1). The Gazzi-Dickinson method is based almost solely on composition (except for the size range between .03 and .0625 mm); thus, results are not influenced by grain size due to the breakage of grains, but are influenced by fundamental compositional differences in grain sizes, as with any point-counting method.

Use of either counting method results in greater similarity of modal composition be-

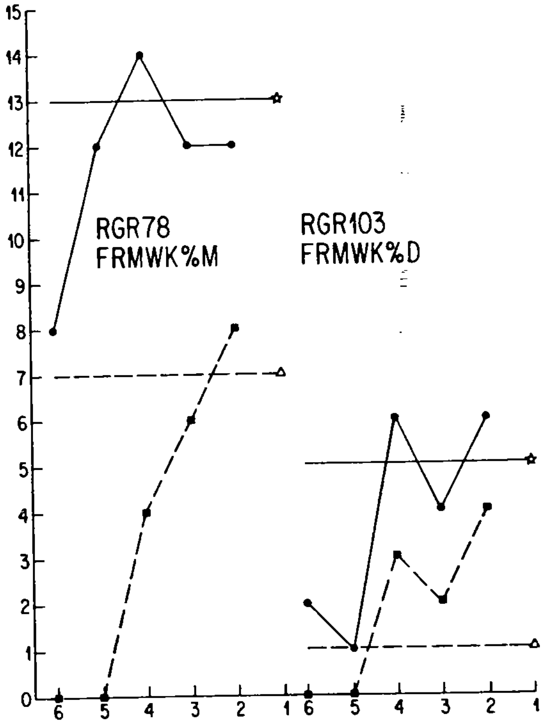

FIG. 6.—Binary plots of framework% phyllosilicates (M) and dense minerals (D) versus grain size. See Figures 1 and 3 for explanation of symbols. Compositional variation with grain size is fairly high using either method, although Gazzi-Dickinson method produces more uniform results for Sample RGR78. The other four samples (RGR66, RGR85, RGR104, and RGR110) produced similar results using both counting methods.

tween coarse-grained and unsorted samples, and less similarity between fine-grained and unsorted samples. This result probably is due to the lesser volume of fine components relative to coarse components of each unsorted sample.

The QFL percentages for each sample are consistently more variable than are the QpLvmLsm and LmLvLs percentages using the traditional method (Figs. 1–4). These results suggest that lithic proportions are better indicators of source rocks than are QFL percentages no matter what method is used. In addition, the Gazzi-Dickinson method provides more consistent results for all parameters. A scarcity of lithic fragments within an unsorted sample using the Gazzi-Dickinson method implies coarse-grained source rocks, whereas using the traditional method, lithic fragments generally are scarce only in fine-grained fractions. Therefore, their absence in an unsorted sample may not have source-rock significance using the traditional method. Recognition of the type of coarse-grained source rocks using either method must rely on a combination of parameters such as QFL, P/F, M, and D, and other techniques such as degree of polycrystallinity of quartz (Basu et al. 1975).

IMPLICATIONS AND CONCLUSIONS

The results of this study show that the Gazzi-Dickinson method of point-counting sand/sandstone has distinct advantages over traditional methods of determining modal compositions for the purpose of differentiating source rocks. The three primary advantages are 1) more uniform results are obtained for any grain size, including unsorted samples; 2) sieving and multiple counts of different fractions are unnecessary; and 3) counts are completed more quickly and with less ambiguity, especially for poorly sorted, diagenetically altered sandstones ("graywackes"). These results are especially significant for the construction and use of actualistic petrologic models because identical petrographic methods can be applied to modern sands and ancient sandstones. Traditional methods that rely on sieving cannot be applied to poorly sorted sandstones because of the variability of grain size and, hence, the variability of composition. In addition, identification of original grain sizes in highly compacted sandstones is extremely difficult, thus rendering impractical the counting of a single grain size within a poorly sorted, compacted sandstone. Use of the Gazzi-Dickinson method provides confidence that similar source rocks will produce similar modal compositions no matter what the grain size or the compactional history of the sediment. Naturally, these generalizations only apply to situations in which other factors such as transportation, depositional environment, and diagenesis are subordinate in importance. Situations where this commonly is the case include areas of active tectonism/magmatism, and rapid accumulation and burial of detritus. Using these methods, actualistic petrologic models relating sand/sandstone composition directly to tectonic setting (for example, Dickinson and Suczek 1979; Ingersoll and Suczek 1979) gain futher credibility. Therefore, we recommend universal use of the Gazzi-Dickinson point-counting method for determining source rocks based on modal composition of sand and sandstone.

ACKNOWLEDGMENTS

Acknowledgment is made by Ingersoll to the donors of the Petroleum Research Fund, administered by the American Chemical Society, for partial support of this research. We thank A. Basu, R. N. Hiscott, G. V. Middleton, C. A. Suczek, L. J. Suttner, and G. G. Zuffa for helpful reviews of the manuscript, without any implication of endorsement of the conclusions!

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DISCUSSIONS

THE EFFECT OF GRAIN SIZE ON DETRITAL MODES: A TEST OF THE GAZZI-DICKINSON POINT-COUNTING METHOD—DISCUSSION[1]

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A more sophisticated interpretation of the total provenance of sand and sandstone, as well as its transportational, depositional, and diagenetic history, is a recent result of our better understanding of the interrelationship between grain size and grain composition. Ingersoll et al. (1984) have recommended universal use of the Gazzi-Dickinson point-counting method (G-D method) for determining source rocks for sands and sandstones. However, such a recommendation, if heeded, will sacrifice the newly developed potential for detailed petrographic interpretations for the sake of expedient collection of data useful only in achieving a single and relatively narrowly defined goal—parent-rock interpretation. Such a sacrifice is unwarranted and unwise.

We agree with Ingersoll et al. that the G-D method provides confidence that similar source rocks will produce similar modal detrital compositions, regardless of grain size. However, the same level of confidence can be achieved if modal compositions are based on a specific grain-size population (e.g., grains of medium sand size). We also agree that the G-D method is more efficient; sieving is not needed and because coarsely crystalline lithic fragments are not identified, little or no need exists for switching back and forth between high and low magnification during modal analysis in order to identify lithic grain types. But sieving can be avoided with routine use of a grid micrometer ocular which permits near instantaneous selection of grains of a specified size. If the crosshairs land on a grain within the size range, it is counted; if not, it is ignored. The size of most grains can be judged quickly, with little practice, using the grid micrometer ocular as a guide, thereby precluding need for detailed measurement. Computerized point counters are also more easily available today, including automated versions (Minnis 1984).

Ingersoll et al. (1984) also demonstrate via ternary plots that the G-D method results in a better clustering of samples with identical source-rock heritage. This is an artifact of projection and fundamentally results from a reduction in variables (i.e., elimination of coarsely crystalline, lithic grains), which they employ in their counting techniques. However, in general, rigor and accuracy in classification are directly related to the total number of variables used. For this reason, ternary composition plots based on G-D data have less overall interpretative value than those based on modal analysis data derived in the traditional way.

Even if the above advantages of the G-D method are significant, we question whether or not they offset the disadvantage of information loss, which is a direct consequence of the G-D counting technique. Consider a suite of sandstones derived exclusively from granitic parent rocks and containing a range in percent of coarsely crystalline granite fragments (i.e., 0–100%). All of these samples would plot on the quartz-feldspar join on a standrd QFL triangular plot if they were analyzed with the G-D method. Conceivably, all could plot at a single point on the join, giving rise to the ultimate in clustering, which Ingersoll et al. (1984) view as an advantage. On the other hand, if the same suite of sandstones was analyzed using traditional counting techniques, individual samples could be plotted anywhere within the ternary diagram. Granted, such a plot by itself would provide a hazier basis for concluding that all of the sands were derived from granite. But it certainly would convey important differences about the *total* history of the samples. The ultimate goal of most sandstone petrology is reconstruction of paleogeology, not tectonic setting alone. Even then, individual tectonic settings are characterized by unique combinations of all of the variables controlling framework composition (e.g., provenance in the broadest sense, length and rigor of transportation, depositional environment(s) and diagenesis), not just parent rock. Because the G-D method permits reliable interpretations of only parent-rock associations, it is inferior to the traditional form of modal analyses.

Our remaining criticisms of the G-D method are, perhaps, more a function of the Ingersoll et al. application of the method, specifically in definition of grain types, than they are an intrinsic trait of the method itself. We find it unacceptable to classify, for example, a detrital grain of sandstone, itself containing smaller volcanic rock fragments, as a volcancic rock fragment if, during counting, the crosshairs land on the contained small grain of volcanic rock. Also, what happens if the grain under the crosshairs is an included crystal, of, say, rutile, in a larger grain of quartz?

Similarly, to count all quartz-mica aggregates as Lm is inappropriate. We have seen many examples of such detrital grains which have been derived from plutonic rocks. And, to add that "the slightest amount of impurities within a chert grain results in the grains being classified as sedimentary lithic grains" is disturbing. Chert by definition *is* a sedimentary rock. Why are impurities needed in order to classify detrital chert grains as sedimentary rock fragments? And what constitutes the "slightest" amount of impurities? Do trace concentrations of iron, for example, qualify? We suspect that the authors are playing loose with their terminology and incorrectly using the word *chert* when they mean crypto- or microcrystalline silica. Furthermore, combining detrital micro- and cryptocrystalline quartz with mono-crystalline quartz to make QFL%Q, as the authors do, should be avoided. Many back-arc sands (e.g., Lower Cretaceous of the western Cordillera) are notably rich (as much as 90%) in micro- and cryptocrystalline silica, but lack significant amounts of feldspar and other lithic fragments. If all of the quartz varieties are lumped in a single class, these sandstones become quartz arenites. This is hardly appropriate and certainly does not reveal the supra-crustal, foreland-fold and thrust-belt source of much of this quartz.

Finally, Ingersoll et al. (p. 106–107) have carelessly and incorrectly applied our definition of detrital rock fragments (Suttner et al. 1981, p. 1236) when they conclude that the definition, upon application, theoretically could result in the mysterious derivation of Lm from Qm through breakage. In the hope that more standardization and rigorous identification will result, we would like to repeat our definition:

> A *rock fragment* is a grain with two or more phases or crystals where (i) no single phase is >90% of the total area of the grain in thin section (commonly applicable to very fine or fine-grained sand grains), or (ii) at least the two phases or crystals are both >0.063 mm in size (commonly applicable to medium or coarse sand grains).

Ingersoll et al. (1984) incorrectly apply only the first criterion when they claim that a coarsely crystalline metamorphic rock fragment consisting of 91% monocrystalline quartz and 9 percent mica (Qm according to the first criterion of our definition (i)), would produce, when broken in half, a modal composition of 50% Qm and 50% Lm (thus, the mysterious derivation of Lm from Qm).

We recommended the second criterion for coarse sand grains precisely to avoid the above! According to our definition, the above grain would be either Lp or Lm, but not Qm. The hypothetical breakage analysis of Ingersoll et al., when applied to a fine-grained fragment consisting of 91 percent quartz and 9% mica (Qm according to definition (i)) would not work either. Although breakage might still result in one quartz-mica aggregate, that is, rock fragment, and Ingersoll et al. (1984) are right in criticizing us, almost always the aggregates would be reduced to silt or finer sizes and thus could no longer be included in standard modal analyses of the sand fraction.

Variation of composition with grain size clearly exists in sand and sandstone and has significance. We should not ignore this for the sake

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[1] Manuscript received 27 November 1984; accepted 27 February 1985.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 55, NO. 4, JULY, 1985, P. 0616–0627
0022-4472/85/0055-0616/$03.00

of adopting a petrographic technique which, at best, improves our ability to decipher source rock and, at worst, sacrifices precision in observation. we are to err, let us do so on the side of too much detail and too little ustering, not on the opposite side, from which recovery is impossible.

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THE EFFECT OF GRAIN SIZE ON DETRITAL MODES: A TEST OF THE GAZZI-DICKINSON POINT-COUNTING METHOD—REPLY TO DISCUSSION OF LEE J. SUTTNER AND ABHIJIT BASU[1]

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Suttner and Basu have raised several important points that warrant specific comment. More importantly, however, their discussion of our paper provides additional exposure to the problems involved in point-counting methodology. Thus, we feel that we have accomplished one of our primary goals: to increase readers' awareness of the necessity for rigorous methodology. Whether or not other workers choose to use the Gazzi-Dickinson (G-D) method should be based on their ultimate goals and their specific problems. Whatever their methods, however, it is essential that they carefully define their criteria for establishing grain parameters, and that they supply as many of the basic data as possible. Our paper has been a success if it encourages more sandstone petrographers to do this.

We agree with Suttner and Basu (and stated so in our paper), that methods other than the G-D method should be used for other applications, such as paleoclimatology. We also agree that the G-D method is a more specialized application of petrography than "traditional" methods. However, we see this as a positive aspect because it allows more refined results. We do, in fact, view improved clustering of data as an advantage if the goal is the discrimination of different groups! The only grain category eliminated with the G-D method is plutonic lithics (Lp), so that improved clustering is accomplished primarily by elimination of "random" variation due to the breakage of grains, rather than to the counting of fewer categories. Also, it is important to note that the most useful plots for discriminating tectonic setting (e.g., QpLvmLsm and LmLvLs) are affected insignificantly by the "projection" effect. Our opinion is that QFL (or QmFLt; see below) percentages have little unambiguous use for paleotectonic reconstructions when used in isolation (e.g., Ingersoll (1983) showed that QFL percentages were the least useful of seven parameters in petrofacies discrimination). Propor- ons of lithic types and secondary parameters (e.g., P/F, Qp/Q) are the ost essential elements. In this context, advanced instrumentation (e.g., Minnis 1984) may improve our mineralogical data-acquisition abilities, but it will not help to identify fine-grained lithic fragments of similar compositions but varying textures.

Use of the G-D method acknowledges that *ultimate* source rocks commonly determine sand/sandstone compositions (e.g., Suttner and Basu's example of Lv in Ls). The presence of Lv in a sandstone may *always* be the result of erosion of an older volcaniclastic sandstone. This is one of the ambiguities of provenance determination generally, *not* of the counting method. The G-D method results in more uniform numerical values (presumably fairly objective); interpretations (more subjective) must be based on *all* available data (including observations that some Lv occurs within Ls, paleoclimatologic inferences, gravel petrology, paleocurrents, etc.). By the same reasoning, sand-sized rutile in quartz should be counted as rutile because rutile in finer sand may *always* have its origin in larger quartz grains that have subsequently been broken. Application of the G-D method should apply to all occurrences regardless of petrogenetic interpretations. Uniform application results in better distinction between objective data and subjective interpretations.

Many of Suttner and Basu's additional comments concern details of parameter definitions, which certainly can be argued by all sides. We admit to loose usage of the term *chert* where we mean "detrital crypto- and microcrystalline silica." However, we would prefer to delete "detrital" because this is an interpretation rather than an objective criterion. We plead guilty to using one short word in place of an awkward phrase in the name of expediency! At least our general category (Qp) is superior to using "C" for all "crypto- and microcrystalline silica."

Suttner and Basu also object to combining Qm and Qp into Q in a QFL triangle. We are quite happy using QmFLt (e.g., Graham et al. 1976) in place of, or preferably in addition to, the QFL plot. However, usage of the QFL plot is unambiguous when combined with other parameters (especially Qp/Q and QpLvmLsm). Use of the QFL plot in isolation is strongly discouraged. Suttner and Basu worry about the fact that use of the G-D method results in the classification of foreland

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[1] Manuscript received and accepted 27 February.

sandstones as "quartz arenites." We are unconcerned with what we consider to be artificial classification schemes; we are more concerned with determining source rocks, and ultimately, paleotectonic settings.

We agree with Suttner and Basu that variation of composition with grain size has significance. However, where variation in composition occurs using the G-D method, we know that it is due to real mineralogic variations among different grain sizes, and not to breakage of grains. Using traditional methods, interpretation of composition variations with grain size is more ambiguous due to two possible sources of variation. By eliminating one source of variation (i.e., breakage of grains), use of the G-D method improves our ability to interpret real mineralogical variations.

We thank Suttner and Basu for the opportunity to clarify our viewpoint, and we commend them and their associates for their pioneering work on paleoclimatological interpretations in particular, and sandstone petrogenesis in general. Our goals and methods have been, and will continue to be, somewhat different. We hope that improved understanding results from this exchange. We feel confident that Suttner and Basu would agree with the following sentence. Gone are the days when a sandstone petrographer could "do" a point count, "classify" the sandstone, and feel that the job is "done."

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THE EFFECT OF GRAIN SIZE ON DETRITAL MODES: A TEST OF THE GAZZI-DICKINSON POINT-COUNTING METHOD—DISCUSSION[1]

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INTRODUCTION

The Gazzi-Dickinson point-counting method differs from the traditional point-counting method in that monomineralic crystals and other grains larger than 0.0625 that occur within larger rock fragments are classified as the crystal or grain, rather than as the larger rock fragment. Ingersoll et al. (1984) recommend "universal use of the Gazzi-Dickinson point-counting method for determining source rocks based on modal composition of sand and sandstone." We disagree with their recommendation for three reasons: (1) the Gazzi-Dickinson method does not effectively reduce the grain size bias of all provenance-diagnostic detrital constituents, (2) counting genetically important rock fragments as monomineralic grains, which may have an uncertain provenance, is counterproductive to the study of sandstone provenance, and (3) the QFL and Q_mFL_t triangular plots produced for sandstones analyzed by the Gazzi-Dickinson method give a misleading view of the composition and maturity of the sandstones. Alternatively, we suggest that grain-size effects should be controlled by analyzing only samples with mean (and ideally, modal) grain size in the medium- to coarse-grained sand range, and that provenance-diagnostic parameters be maximized by tabulating all clasts encountered within the sand range.

OBJECTION 1: EFFECT OF GRAIN SIZE

The effect of grain size on the detrital composition of sandstone has been recognized for many years. Boggs (1968) and Ingersoll et al. (1984) have demonstrated that, in most cases, polycrystalline rock fragments are more abundant in the coarser sand sizes than in the finer sand sizes. There are basically two ways to reduce the effect of grain size on the rock-fragment population. The first is to point count using the Gazzi-Dickinson method, and the second is to restrict the grain size of the samples analyzed. The Gazzi-Dickinson method, however, fails to reduce the grain-size effect on the provenance-diagnostic properties of monomineralic grains, namely, undulosity and polycrystallinity of quartz grains, and the A-twin/C-twin ratio and zoning in plagioclase. Basu et al. (1975) and Young (1976) describe the utility of undulosity and polycrystallinity in quartz grains as provenance indicators, and studies by Blatt (1967a, b), Conolly (1965), and Basu et al. (1975) show the strong dependence of these parameters on mean grain size. Twinning and zoning of feldspars are useful as provenance indicators (Pittman 1963, 1970), and these properties are also strongly dependent on grain size (Pittman 1969). The only way to reduce the grain-size dependence of these monomineralic grains and thus allow comparisons between samples and between studies, is to restrict the grain-size interval of the counted samples. We favor the medium to coarse sand size for four reasons: (1) this grain size is abundant and commonly preserved in the ancient record, (2) it is the optimum grain size for microscopic observation (high magnification can be used to study the internal features of grains while still allowing observation of grain shape), (3) this grain size affords the best comparison with published provenance studies, and (4) it preserves the most rock-fragment information without decreasing the number of grains in a standard thin section to an unacceptably low level.

Dickinson and Rich (1972) used medium- to coarse-grained sandstones for defining petrofacies in the Great Valley Sequence of California, and stated that "finer-grained rocks are unsuitable for detailed optical work." The important point is that much provenance information is contained in microphaneritic (Dickinson 1970) rock fragments, and it is, therefore, unwise to eliminate these data by restricting the internal grain size of rock fragments to the silt and clay size ranges.

OBJECTION 2: PROVENANCE

The most important goal of a sandstone provenance study is to reconstruct the source terrane of the sandstone. Rock fragments, being recognizable pieces of the source terrane, provide the best clue to an accurate reconstruction. We disagree with the statement of Ingersoll et al. (1984) that the Gazzi-Dickinson method "attempts to maximize information regarding source rocks"; in fact, we believe just the opposite. To count genetically significant rock fragments as monomineralic

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[1] Manuscript received 21 December 1984; accepted 27 February 1985.

grains of possibly uncertain provenance, as the Gazzi-Dickinson method requires, is counter-productive to the provenance study. Failure to study and tabulate rock-fragment information whenever possible is the critical flaw in the Gazzi-Dickinson method.

Ingersoll et al. (1984) further state that the Gazzi-Dickinson method "is faster because the [microscope] operator does not have to determine in what kind of grain a sand-sized crystal occurs." In reality, it is often faster and more accurate to identify microphaneritic rock fragments than the very fine to fine sand-sized crystals that comprise these grains. Additionally, considerable time is spent by the operator using the Gazzi-Dickinson method in determining whether crystals within rock fragments are coarser than 0.0625 mm (lower sand limit).

Ingersoll et al. (1984) argue that the Gazzi-Dickinson method retains provenance informtion contained in rock fragments by use of the $Q_pL_{vm}L_{sm}$ diagram. Comparison of their figures 1 and 2 shows that this is true only for sandstones rich in aphanitic rock fragments. Their samples RGR78 and RGR85 do not appear in the $Q_pL_{vm}L_{sm}$ diagram (their fig. 2) "because each has so few lithic fragments [when counted by the Gazzi-Dickinson method] that this plot is statistically insignificant." Examination of their table 2, however, shows that the detrital fractions of these same two sandstones contain 76 and 50% plutonic lithic fragments, respectively, when counted by the traditional method. It is apparent that provenance information contained in microphaneritic rock fragments is lost when sandstones are counted by the Gazzi-Dickinson method.

OBJECTION 3: COMPOSITION AND MATURITY

Counting monomineralic crystals within a rock fragment instead of the rock fragment itself has the adverse effect of misrepresenting the actual detrital composition of the sample, and overestimating its mineralogical maturity. This counting procedure generally causes quartz and feldspar to be overrepresented and rock fragments to be underrepresented in the detrital modes. Point-count data from six samples listed in table 2 of Ingersoll et al. (1984) show that by using the Gazzi-Dickinson method, total quartz is increased an average of 22.9% and feldspar 13.6% over the actual clast composition, as determined using the traditional method. Their sample RGR78 of "coarse schist" is a good example of misclassification caused by use of the Gazzi-Dickinson method. In their figure 1, the unsorted sample counted by the traditional method plots at $Q_{15}F_2L_{83}$ very near the L pole and would be classified as a lithic sandstone, whereas the unsorted sample counted by the Gazzi-Dickinson method plots at $Q_{60}F_{39}L_1$ very near the Q-F line and would be misclassified as an arkose. (Note that RGR78 is a very curious sample. It is derived from coarse schist, yet the predominant internal crystal size of the clasts derived from this rock is apparently in the range 0.0625 mm to 0.125 mm, nearly all of which were counted by Ingersoll et al. (1984) as plutonic rock fragments (L_p) using the traditional method!) The mineralogical maturity of a sandstone is defined as the ratio of total quartz grains to feldspar grains plus unstable rock fragments (Pettijohn 1975). When quartz crystals within rock fragments are tabulated with quartz instead of with rock fragments, the percentage of quartz grains is artificially increased, producing an overestimation of the maturity of the sample. Sample RGR78, discussed above, is a good example of an apparent increase in maturity due to the counting method.

We agree with the statements of Ingersoll et al. (1984) that "the Gazzi-Dickinson method is based almost solely on [mineral] composition" and that "petrologists interested in diagenesis employ different techniques than do those interested in paleoclimates or source rocks." We would suggest, however, that the Gazzi-Dickinson method is a more appropriate point-counting technique for those petrologists interested in studying diagenesis than for those concerned with deciphering the provenance of sandstones. It is well established that feldspars and aphanitic rock fragments (particularly volcanic rock fragments) are chemically and mechanically less stable in the diagenetic environment than quartz (Hayes 1979). From a diagenetic standpoint, therefore, it may be important to know the volumetric proportion of quartz and feldspar in a sandstone regardless of whether they occur as monocrystalline grains or as crystals incorporated in rock fragments. The procedure of counting microphaneritic rock fragments as monomineralic grains makes the Gazzi-Dickinson method useful in diagenetic studies where chemical stability of the detritus is of more concern than its provenance.

CONCLUSIONS

Our principal objection to the Gazzi-Dickinson point-counting method concerns the technique of counting microphaneritic rock fragments as their component crystals and grains instead of as rock fragments. We fully support and use the majority of the concepts outlined by Dickinson (1970). Most importantly, we are in complete agreement with Dickinson's stated purpose of providing a "firm interpretative base from which to advance." Standardization is an important goal in all scientific procedures, and point-count analysis is no exception. The Gazzi-Dickinson method, however, standardized at a lower level than is acceptable for detailed provenance studies.

We feel that the main utility of the Gazzi-Dickinson point-counting method is in studies of thick sedimentary sequences in which the sandstones show systematic stratigraphic variations in grain size and where the goal is to determine if the sandstones share a common provenance. It is also useful in diagenetic studies where chemical stability of the detritus is a major concern. If, however, the goal is to determine the provenance of the sandstones, then the traditional point-counting method should be employed on the medium- to coarse-grained sandstones. For some studies, it may be appropriate to use both point-counting methods.

Our final comment concerns the use of summary categories (e.g., Q_p, L_v, L_s) as counting categories. We realize that Ingersoll et al. (1984) counted summary categories to focus on comparing the two point-counting methods, but we oppose the general use of this procedure in provenance studies. The ability to plot sandstone compositions on the four triangular diagrams (QFL, Q_mFL_t, $Q_pL_vL_s$, Q_mPK) utilized by Dickinson and Suczek (1979) to infer tectonic setting requires only six counted categories (Q_m, Q_p, L_v, L_s, P, and K). A superficial analysis of this type runs the risk of overlooking critical information required to interpret the data correctly. Only through detailed evaluation can the provenance be determined and the inferred tectonic setting be corroborated or refuted. Mack (1984) has shown several cases of sandstones that plot in erroneous tectonic fields on the triangular diagrams of Dickinson and Suczek (1979) that, however, were correctly interpreted through detailed study. Again, we agree with Dickinson (1970) who states that "interpretations that are too superficial or generalized no longer have the potential to stimulate fresh thinking."

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THE EFFECT OF GRAIN SIZE ON DETRITAL MODES: A TEST OF THE GAZZI-DICKINSON POINT-COUNTING METHOD—REPLY TO DISCUSSION OF JOHN DECKER AND KENNETH P. HELMOLD[1]

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INTRODUCTION

Some of our more general responses to Suttner and Basu also apply to Decker and Helmold's discussion of our paper. Therefore, we limit ourselves herein to replying to specific points made by Decker and Helmold.

OBJECTION 1: EFFECT OF GRAIN SIZE

We agree with Decker and Helmold that use of the Gazzi-Dickinson method does not eliminate the dependence of composition on grain size and that certain properties (e.g., undulosity of quartz), which are grain-size dependent, are unaffected by use of the Gazzi-Dickinson method. Therefore, studies of polycrystallinity of quartz, twin ratios and zoning of feldspar, and other provenance studies can proceed with or without use of the Gazzi-Dickinson method. These are studies of the characteristics of individual minerals rather than of fine-grained lithic fragments. We encourage these types of studies. We also favor the sampling of medium to coarse sand or sandstone (e.g., Ingersoll 1978). However, medium to coarse sand/sandstone is not always available, and poorly sorted sand/sandstone may contain a wide range of grain sizes.

We object to Decker and Helmold's statement that provenance information contained in microphaneritic fragments is eliminated using the Gazzi-Dickinson method. The information is simply transformed. Is more information conveyed by saying a sandstone consists of 100% plutonic fragments (traditional) or by saying it consists of 40% monocrystalline quartz, 30% potassium feldspar and 30% plagioclase feldspar (Gazzi-Dickinson)? We find the latter more informative. However, we repeat our statement that "separate note may be made of the relative percentage of discrete grains versus phenocrysts or microphanerites if this information is deemed useful. (Rarely does this type of information provide source-rock data that are not already known from the standard counts using this method.)" (Ingersoll et al. 1984, p. 106).

OBJECTION 2: PROVENANCE

The above example of a plutoniclastic sandstone illustrates how Decker and Helmold's statement can be turned around, as follows: "Failure to study and tabulate mineralogical information whenever possible is the critical flaw in the traditional method." We do not subscribe to this statement any more than we do to theirs. *All* provenance information should be utilized in any study. We have discussed our philosophy regarding this in our reply to Suttner and Basu.

Good staining of thin sections and experience allow the skilled petrographer to identify sand-sized mineral grains rapidly and accurately.

Decker and Helmold state "that provenance information contained in microphaneritic rock fragments is lost" because they do not appear on some kind of lithic-fragment plot. As in the above case, the information is not lost, it merely appears in a different form (e.g., QmPK plot or P/F ratio). We can reverse the argument and claim that provenance information is lost using the traditional method because the above plutoniclastic sandstone cannot be plotted on a QmPK plot. Again, the information is not "lost," it is transformed (into easily used data).

OBJECTION 3: COMPOSITION AND MATURITY

We dislike the tone of Decker and Helmold's third objection because it implies that somehow use of the traditional method produces "actual" results, whereas use of the Gazzi-Dickinson method "overestimates," "artificially increases," and "misclassifies." This is a narrow viewpoint based on tradition, *not* on any absolute truth. *All* modal compositions are functions of definitions and counting methodology. The "Indiana" method (e.g., Suttner and Basu's discussion) differs in some ways from our "traditional" method, and there are certainly other methods. No method is "correct." All methods have been developed with some purpose in mind. Pettijohn's (1975) definition of mineralogical stability is based on the assumption that a "rock fragment" has a traditional definition. We are careful to point out that we do not count "rock fragments" in the traditional sense. We count "aphanitic lithic fragments."

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[1] Manuscript received and accepted 27 February 1985.

Something can be "misclassified" only within the frame of reference of artificially constructed classification systems.

Decker and Helmold note that "RGR78 is a very curious sample," presumably because it is a schist consisting of plutonic rock fragments (traditional method). In this particular case, "coarse schist" might have been replaced by "gneiss," and the apparent contradiction in results would be more understandable. Differentiating high-grade metamorphic provenance from plutonic provenance is usually a challenging task with many ambiguities, using any method.

We are pleased to see that Decker and Helmold find the Gazzi-Dickinson method to be possibly more appropriate than other methods in diagenetic studies. Maybe we should suggest universal use of the Gazzi-Dickinson method for *all* studies, and not just source-rock studies!

CONCLUSIONS

We are honestly mystified by Decker and Helmold's statement that the "Gazzi-Dickinson method standardized at a lower level than is acceptable for detailed provenance studies." Does this mean that their method "standardized at a higher level"? We reiterate the point made in our original paper and in our other reply that no method is necessarily better than another, except within the context of the goals of a study, and the efficiency and accuracy with which those goals are obtained.

We are in total agreement with Decker and Helmold's last quotation from Dickinson (1970). Interpretation of provenance is a tricky business and superficial analyses are to be avoided. We recommend against the use of Dickinson and Suczek's (1979) four triangular plots in isolation from other types of data. "Detailed evaluation" includes precise definition of point-counting methods, whatever they are. We thank Decker and Helmold for the opportunity to further emphasize and clarify our use of the Gazzi-Dickinson method.

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A VISUAL COMPARATOR FOR DEGREE OF SORTING IN THIN AND PLANE SECTIONS—DISCUSSION[1]

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Line drawings are an important type of scale model. They allow quick, reasonably accurate visual estimation of values that can be determined more precisely but more laboriously by other methods. Venerable, often-used examples include grain angularity (Powers 1953, p. 118, which is reproduced in many texts and lab manuals; also Pettijohn 1975, p. 57; 1957, p. 59; Russell and Taylor 1937, p. 239), grain shape (Zingg 1935, as illustrated in many textbooks and laboratory manuals on sediments and sedimentary rocks), and percentage of composition (Terry and Chilingar 1955, p. 230–233). Thus, the visual comparators (scale-model line drawings) offered by Harrell (1984) for estimating sorting coefficient in thin section and plane section would be a valuable contribution were they not based on inappropriate statistics.

Most analyses of size distribution in sediments and sedimentary rocks are based on sieve, settling-tube, and thin-section measurements. Sieve and settling-tube measurements are in the form of weight of grains per size class, not number of grains per size class; for analysis, these raw data are converted to weight percentage. Thin-section measurements initially appear to be in the form of number of grains per size class. However, the thin-section technique employs a square grid (ideally larger than the largest grain present) to randomly sample grains independently of their size but proportional to their areal (volumetric) abundance (Van der Plas and Tobi 1965); therefore, the data are actually in the form of area percentage. There is a very strong, positive correlation between area percentage, volume percentage, and weight percentage for most sediments and sedimentary rocks because the great majority of sedimentary particles have similar shapes and density values. Consequently, sedimentologists and sedimentary petrologists use size-distribution parameters, for example, mean and sorting, to describe weight or volume distribution, and expect that terms, such as coarse-grained, well-sorted, and log-normal, also describe weight or volume distribution.

Harrell (1984) used individual-abundance statistics, not volume- or weight-abundance statistics; the histograms in his Figure 1 display "number of spheres" per class, and on p. 647, the equation used to calculate the standard deviation, S, is based on the "number of spheres." Unless all grains within a sample are exactly the same size, distribution parameters (i.e., mean, median, sorting, skewness, and kurtosis) calculated on the basis of individual abundance differ from those calculated on the basis of volume or weight abundance. Consequently, only the visual comparator in figure 2 of Harrell (1984) shows sedimentologists and sedimentary petrologists what it claims: namely, a slice through a sample with a sorting coefficient of 0.0 phi units. An essentially equivalent image was first published by Graton and Fraser (1935, p. 848) and has been reproduced in Carver (1971, p. 96) and in Williams et al. (1954, p. 284; 1982, p. 309). None of the four samples in Harrell's Figure 1 and illustrated in his Figures 3, 4, 5, and 6 show what they purport. All four are better sorted than claimed. The samples in his Figures 4, 5, and 6 (S = 0.50, 1.00, and 2.00, respectively) are all positively skewed and not log-normal.

The differences between volume-abundance and individual-abundance distributions are displayed in Figures 1 and 2. Figure 1 compares the histograms of all five samples from Harrell (1984), which are based on number of grains per class, with histograms based on calculated volume of grains per class (volume per class = $n4\pi r^3/3$). The volume-abundance histograms are offset −0.25 phi units relative to the individual-abundance histograms to correspond with the manner in which these data are normally presented and are, except for the perfectly sorted sample's histogram, asymmetrical and weighted toward the coarse tail. Figure 2 compares log-probability plots of all five individual-abundance samples with those based on calculated volume abundance. Four of the five log-probability plots are necessarily offset by −0.25 phi units. Only for the perfectly sorted sample are the two differently based log-prob-

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[1] Manuscript received 10 October 1984; revised 8 March 1985.