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QUANTITATIVE ANALYSIS OF VOLCANIC LITHIC FRAGMENTS

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ABSTRACT: Textural subcategories of volcanic lithic fragments in sand and sandstone have been correlated qualitatively with volcanic compositional types, but these relationships have not been tested quantitatively. Lathwork grains were assumed to be derived mainly from mafic lavas, microlitic from intermediate lavas, and felsitic (sometimes divided into granular and seriate) from silicic lavas. Vitric volcanic lithic fragments were not initially assigned a composition, but they commonly have been associated with silicic compositions. More precise definitions of volcanic lithic types facilitate the quantification of modal proportions of these types, which can be used to test correlations between lithic type and SiO₂ content of volcanic rocks. In order to establish which types of volcanic lithic fragments are produced by volcanic rocks of specific compositions, 94 thin sections from diverse volcanic rocks with 45.57 to 76.93 weight % SiO₂ were counted using the Gazzi-Dickinson point-counting method. Relationships between volcanic lithic-fragment type and SiO₂ content are complex. The only definitive conclusion is that samples containing dominantly vitric and granular volcanic lithic fragments can be confidently assigned to high-SiO₂ sources. More tentative conclusions are that mafic volcanic rocks have lithic types anywhere on the seriate–microlitic–lathwork spectrum, and that intermediate volcanic rocks dominantly consist of microlitic and lathwork textures.

INTRODUCTION

Subcategories of volcanic lithic fragments in sand and sandstone were rigorously defined by Dickinson (1970), and further resolved and detailed by Ingersoll and Cavazza (1991) and Large and Ingersoll (1997). Most studied volcanic lithic fragments produced in young volcanic provinces are associated with magmatic arcs (e.g., Dickinson and Suczek 1979; Maynard et al. 1982; Cawood 1983; Marsaglia and Ingersoll 1992; Garzanti et al. 1996; Weltje 2006; Morrone et al. 2017), but also with continental rifts (e.g., Ingersoll 1990; Ingersoll et al. 1993; Lozinsky 1994). Even though volcanic lithic fragments are chemically reactive (Coombs 1954; Surdam and Boles 1979) and prone to compaction (Pittman and Larese 1991), they are still useful in provenance studies, because textures can be preserved and identified even after significant alteration (e.g., Pederson et al. 2000).

Dickinson (1970) suggested that subcategories within the umbrella of volcanic lithic fragments (lathwork, microlitic, and felsitic) represented specific volcanic rock compositions. Lathwork grains (Lvl) were assumed to be derived mainly from mafic lavas, microlitic (Lvm) from intermediate lavas, and felsitic (Lv_f, sometimes divided into granular and seriate) from silicic lavas. Vitric volcanic lithic fragments (Lv_v) were not initially assigned a composition, but they commonly have been associated with silicic compositions (Ingersoll and Cavazza 1991). This correlation between volcanic lithic fragments and volcanic source rocks has been used successfully in many provenance studies (e.g., Corrigan et al. 1990; Critelli et al. 1997, 2002; Large and Ingersoll 1997; Marsaglia et al. 1999). Despite these successes, two major shortfalls exist with respect to these subcategories. First, the subcategories are defined qualitatively, which produces differences among studies. Second, correlation between types of

lithic fragments and compositions of volcanic rock has not been empirically established over the full range of volcanic compositions, although some corroborating evidence has been developed (e.g., Marsaglia 1993). The present study attempts to quantify the definition of volcanic lithic fragments and evaluates correlations with compositions of volcanic rocks.

DEFINITIONS

We quantified the original definitions of volcanic lithic fragments as much as possible, while agreeing with the qualitative textural definitions of previous studies. Overall textures (e.g., Dickinson 1970; Ingersoll and Cavazza 1991) have been defined chiefly on the presence of three main crystalline types: 1) volcanic glass or altered volcanic glass; 2) euhedral to subhedral microlites of various minerals (typically feldspar); and 3) anhedral microlites of various minerals (typically feldspar or quartz) (Fig. 1). Another crucial crystalline type is plagioclase (or other) laths, which by definition are coarser than 0.0625 mm (Dickinson 1970); therefore, individual laths are not counted as lithic fragments because the constituents of lithic fragments, by definition, have components finer than sand, using the Gazzi-Dickinson point-counting method (Ingersoll et al. 1984; see below). Some of the original textural descriptors found in Dickinson (1970), like intersertal and hyalopilitic, are not easy to quantify, and therefore, were not used in this study. However, percentages of easily identifiable components, like microlites and glass, can be linked to specific volcanic lithic types, and are more useful in quantifying and standardizing the use of volcanic lithic fragments in provenance studies.

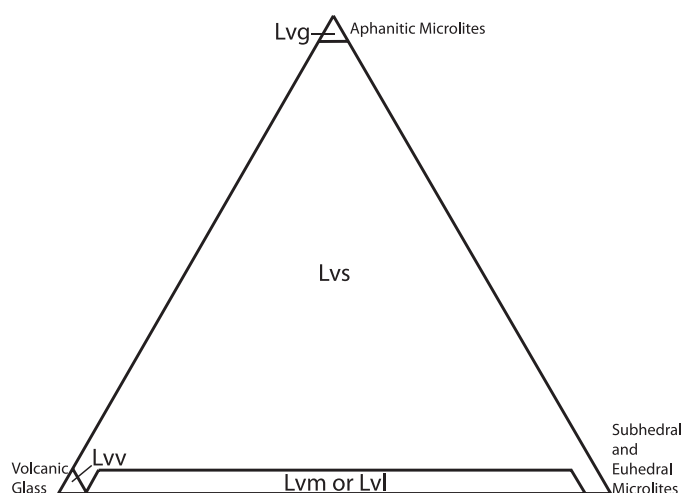


FIG. 1.—Triangular plot showing proportions of volcanic glass, aphanitic microlites, and subhedral and euhedral microlites that define volcanic textural types (Lvv, Lvlg, Lvs, Lvm, and Lvl). All internal lines are at 5% or 95%. See text for discussion.

Vitric Lithic Fragments

Vitric lithic fragments (Lvv) (Fig. 2A) are defined similarly in most studies, as glass or altered glass. We define vitric lithic fragments as consisting of 95–100% volcanic glass and 0–5% aphanitic, subhedral or euhedral microlites. The addition of up to 5% of microlites into vitric lithic fragments is to add a buffer, so that a very minor component of the lithic fragment does not change its classification.

Felsitic Lithic Fragments

Felsitic lithic fragments (Lvlg), as first defined by Dickinson (1970), have two subcategories, granular (Lvlg) (Fig. 2B) and seriate (Lvs) (Fig. 2C), whose differentiation is useful in specific studies (e.g., Ingersoll and Cavazza 1991). Dickinson (1970, p. 701) defined felsitic lithic fragments as “anhedral microcrystalline mosaic, either granular or seriate.” We define granular lithic fragments as consisting of 95–100% aphanitic microlites and 0–5% volcanic glass and subhedral to euhedral microlites. Seriate lithic fragments, which have the broadest definition, even being used as a catch-all in some studies, are defined as consisting of 0–95% volcanic glass, 0–95% aphanitic microlites, and 0–100% subhedral and euhedral microlites.

Microlitic Lithic Fragments

Microlitic lithic fragments (Lvm) (Fig. 2D) are similarly described in most studies, with subhedral to euhedral plagioclase microlites embedded in volcanic glass. Thus, microlitic lithic fragments consist of 5–95% volcanic glass, 5–95% subhedral to euhedral microlites (most commonly plagioclase), and 0–5% aphanitic microlites.

Lathwork Lithic Fragments

Lathwork lithic fragments (Lvl) (Fig. 2E) are similar to microlitic lithic fragments, with the exception of including laths coarser than 0.0625 mm. Some authors have described lathwork textures as gradational with microlitic textures (Ingersoll and Cavazza 1991), with the only difference being crystal size (i.e., microlitic lithic fragments contain crystals less than 0.0625 mm, lathwork lithic fragments contain at least one crystal larger

than 0.0625 mm). Laths are not counted as a component of the grain, but the lithic fragments are defined by their presence. Therefore, the components of lathwork lithic fragments are the same as microlitic: 5–95% volcanic glass, 5–95% subhedral to euhedral microlites, and 0–5% aphanitic microlites, with the additional requirement that at least one lath be present. Also, most authors refer to plagioclase as the laths in lathwork grains. While plagioclase may be the most common lath, this study has used any crystal coarser than 0.0625 mm as a defining characteristic for lathwork grains.

METHODS

In order to establish which types of volcanic lithic fragments are produced by volcanic rocks of specific compositions, zero-order analyses (Ingersoll 1990; Devaney and Ingersoll 1993) were conducted by counting 500 points per sample of thin sections of extrusive igneous rocks. Gazzi-Dickinson point counting (Gazzi 1966; Dickinson 1970, as refined by Ingersoll et al. 1984; Zuffa 1985; Ingersoll et al. 1993) was used on volcanic rocks of known chemical composition in order to quantify which volcanic lithic fragments would be produced should these rocks be weathered and eroded. An area of approximately 1 mm² in the sample of igneous rock was used as a proxy for a sand grain because it is the standard point-count size used to minimize grain-size effects on composition in sandstone (Ingersoll et al. 1984). All components of the rock were counted, including laths. Although most volcanic rocks are homogeneous, where more than one lithic-fragment type was present within the 1 mm², the area that the crosshairs of the petrographic microscope landed was used, as long as the area in question reached the sand threshold of 0.0625 mm.

This study examined thin sections of 94 samples from previous, unrelated studies of volcanic rocks from the Lesser Antilles, New Zealand, and the Snake River Plain, Montana and Wyoming, USA (Table 1). Each thin section was from an extrusive igneous rock with known geochemistry. Silica compositions varied from a low of 45.57 to a high of 76.93 weight % SiO₂ (Fig. 3).

ANALYSIS

Proportions of volcanic lithic-fragment types were plotted against silica content for each point count in order to determine correlations between lithic fragment type and composition (Fig. 4), which demonstrates that relationships are complex. The only clear relationship is that the dominance of vitric lithic fragments is common only in high-silica volcanic rocks. Also of note is the abundance of data at the top and bottom of the graph, indicating that most volcanic rocks consist of a single volcanic lithic-fragment type (zero values, which are common, are excluded from Figure 4 for clarity).

To further test relations between volcanic lithic types and volcanic source-rock compositions, we separated the samples into three groups, based on their SiO₂ content. Using U.S. Geological Survey guidelines for classifying volcanic rocks based on silica content (<https://volcanoes.usgs.gov/vsc/glossary/igneous.html>), our samples were divided into: mafic volcanic < 52% SiO₂, intermediate volcanic 52–63% SiO₂, and silicic volcanic > 63% SiO₂. Relative proportions of lithic types were calculated using raw petrographic data of all categories and subcategories (i.e., Lvv, Lvlg, Lvs, Lvm, and Lvl) (Table 1), which were logratio transformed following the methods of Weltje (2002, 2004) and Ingersoll and Eastmond (2007). Stepwise discriminant analysis (SPSS, 2000) was used to test for groupings of petrographic parameters within each of the three groups. The most stable associations of parameters resulted when Lvv and Lvlg were combined to form Lvlg, and Lvm and Lvl were combined to form Lvml, resulting in three variables (Fig. 5), which defined three groups (Fig. 6). Samples were moved from one group to the neighboring group if they were within 1% SiO₂ of the boundary between the two groups and the

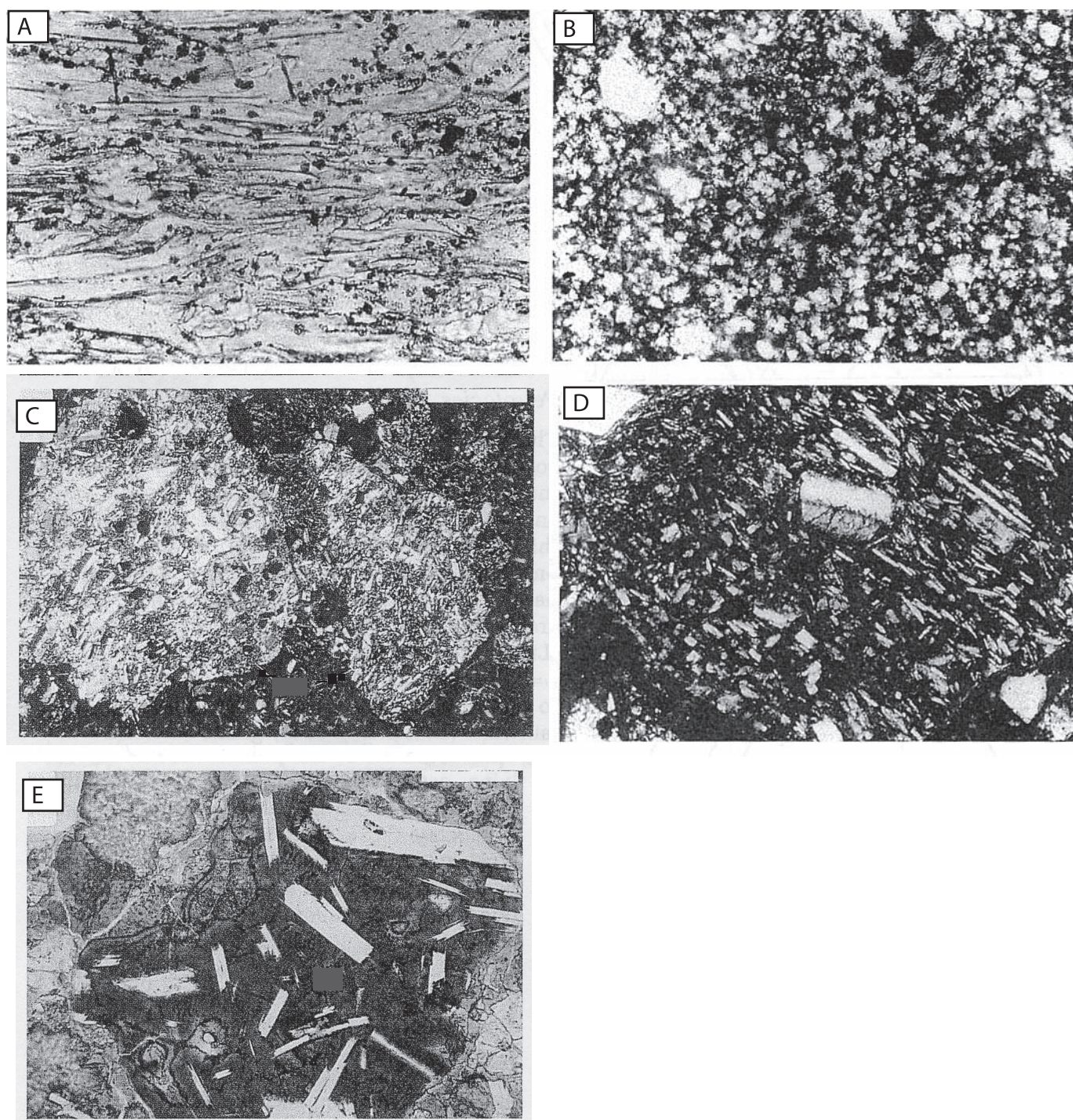


FIG. 2.—Photomicrographs of five volcanic lithic types of Dickinson (1970). **A)** Vitric grain (Lvv) showing flow patterns, plane-polarized light. **B)** Felsitic (granular) grain (Lvg) showing chert-like texture, crossed nicols. **C)** Felsitic (seriate) grains (Lvs) with irregular mosaic of crystals and glass, crossed nicols. **D)** Microlitic grain (Lvm) with abundant plagioclase feldspar microlites, crossed nicols. **E)** Lathwork grain (Lvl) with plagioclase laths, crossed nicols. Picture width is 0.5 mm in A, B, and D (from Ingersoll and Cavazza 1991); scale bar in upper right is 0.2 mm in C and E (from Critelli and Ingersoll 1995).

discriminant function indicated they were misclassified. Multiple runs resulted in the most stable boundaries at $51 \pm 1\%$ SiO_2 and $63 \pm 1\%$ SiO_2 . In other words, neither of the two boundaries between the three groups (mafic, intermediate, and silicic) overlap by more than 2% SiO_2 . Table 2 indicates that 87% of the samples are correctly classified (according to SiO_2) based on multivariate factors, as illustrated in Figure 6.

Triangular plots of Lvvg, Lvs, and Lvml proportions for each of the three groups determined by discriminant analysis provides another perspective on the usefulness of lithic-fragment types in provenance studies (Fig. 7). The only group that contains high proportions of Lvvg are silicic volcanic rocks. Mafic volcanic rocks have the lowest Lvvg values, with diverse mixtures of Lvs and Lvml. Intermediate volcanic rocks are

TABLE 1.—Point-count data of volcanic lithic types sorted by %SiO₂. Also indicated are petrofacies determined by discriminant analysis. Lvv, vitric volcanic lithics; Lvg, granular volcanic lithics; Lvs, seriate volcanic lithics; Lvm, microlitic volcanic lithics; Lvl, lathwork volcanic lithics; LvT, total volcanic lithics; Lvvg, vitric and granular volcanic lithics; Lvml, microlitic and lathwork volcanic lithic.

Petrofacies	%SiO ₂	Lvv	Lvg	Lvs	Lvm	Lvl	LvT	Lvvg	Lvml
Mafic	45.57	0	0	27	367	93	487	0	460
Mafic	45.90	0	0	433	0	0	433	0	0
Mafic	46.41	0	0	17	369	1	387	0	370
Mafic	46.99	0	0	90	315	18	423	0	333
Mafic	47.07	0	0	51	408	1	460	0	409
Mafic	47.42	0	0	42	432	0	474	0	432
Mafic	47.49	0	0	438	0	0	438	0	0
Mafic	47.62	0	0	286	202	2	490	0	204
Mafic	47.71	0	0	406	28	0	434	0	28
Mafic	47.92	0	0	451	22	0	473	0	22
Mafic	47.93	0	0	56	294	1	351	0	295
Mafic	47.93	0	0	107	210	2	319	0	212
Mafic	47.99	0	0	472	7	0	479	0	7
Mafic	48.10	0	0	455	0	0	455	0	0
Mafic	48.42	0	0	120	326	9	455	0	335
Mafic	48.53	0	0	413	22	0	435	0	22
Mafic	48.64	0	0	278	0	0	278	0	0
Mafic	48.65	0	0	462	13	0	475	0	13
Intermediate	49.60	1	2	11	172	230	416	3	402
Intermediate	50.03	0	0	4	267	39	310	0	306
Mafic	51.68	0	0	243	101	128	472	0	229
Intermediate	53.47	0	0	0	259	0	259	0	259
Intermediate	54.00	0	0	6	35	304	345	0	339
Intermediate	55.00	0	0	8	327	2	337	0	329
Intermediate	55.06	0	1	0	92	214	307	1	306
Intermediate	55.06	1	0	0	75	243	319	1	318
Intermediate	55.19	0	0	1	10	313	324	0	323
Intermediate	55.44	0	0	2	66	248	316	0	314
Intermediate	55.71	1	0	4	8	322	335	1	330
Intermediate	55.81	0	0	27	397	0	424	0	397
Intermediate	55.82	2	2	2	0	386	392	4	386
Intermediate	56.25	0	0	1	346	1	348	0	347
Intermediate	56.27	0	0	11	404	2	417	0	406
Intermediate	56.51	0	3	1	0	353	357	3	353
Intermediate	56.71	10	25	6	11	349	401	35	360
Intermediate	56.93	0	10	9	334	7	360	10	341
Intermediate	57.40	0	0	0	453	0	453	0	453
Intermediate	57.79	0	0	12	381	0	393	0	381
Intermediate	58.01	0	0	39	354	0	393	0	354
Intermediate	58.38	0	0	12	318	58	388	0	376
Intermediate	58.42	0	0	11	11	374	396	0	385
Intermediate	58.50	0	0	3	21	395	419	0	416
Intermediate	58.60	0	0	19	260	72	351	0	332
Intermediate	58.75	0	0	9	383	4	396	0	387
Intermediate	58.80	0	0	4	385	0	389	0	385
Intermediate	58.94	0	1	309	36	0	346	1	36
Intermediate	59.02	0	0	12	429	1	442	0	430
Intermediate	59.05	0	0	9	400	4	413	0	404
Intermediate	59.07	0	0	2	474	1	477	0	475
Intermediate	59.14	3	0	0	18	225	246	3	243
Intermediate	59.39	0	0	189	144	0	333	0	144
Intermediate	59.51	0	0	0	399	10	409	0	409
Intermediate	60.26	0	0	1	1	331	333	0	332
Intermediate	60.36	0	0	21	326	1	348	0	327
Intermediate	60.47	71	0	0	0	343	414	71	343
Intermediate	61.05	0	0	4	380	2	386	0	382
Intermediate	61.10	0	0	0	296	1	297	0	297
Intermediate	61.34	0	0	1	116	263	380	0	379
Intermediate	62.09	0	0	7	415	0	422	0	415

TABLE 1.—Continued.

Petrofacies	%SiO ₂	Lvv	Lvg	Lvs	Lvm	Lvl	LvT	Lvvg	Lvml
Silicic	62.10	0	194	33	0	0	227	194	0
Intermediate	62.16	0	0	0	2	359	361	0	361
Intermediate	62.54	0	0	0	0	417	417	0	417
Intermediate	62.60	0	0	12	374	0	386	0	374
Intermediate	62.78	0	0	4	13	350	367	0	363
Intermediate	62.85	0	0	8	426	0	434	0	426
Intermediate	62.86	0	0	1	260	0	261	0	260
Silicic	63.20	0	6	335	0	0	341	6	0
Intermediate	63.56	0	0	18	371	0	389	0	371
Silicic	63.71	0	0	233	137	1	371	0	138
Intermediate	63.76	0	0	1	264	0	265	0	264
Intermediate	63.83	0	0	0	401	0	401	0	401
Intermediate	63.84	0	0	1	310	32	343	0	342
Intermediate	64.29	0	0	13	357	0	370	0	357
Silicic	64.43	0	0	26	412	0	438	0	412
Silicic	65.42	0	0	326	4	0	330	0	4
Silicic	65.49	0	186	64	0	0	250	186	0
Silicic	65.70	0	0	30	336	0	366	0	336
Silicic	65.98	7	0	2	1	271	281	7	272
Silicic	66.23	1	0	0	3	254	258	1	257
Silicic	66.57	0	0	362	0	0	362	0	0
Silicic	67.07	0	0	315	0	0	315	0	0
Silicic	68.43	0	0	1	382	0	383	0	382
Silicic	68.95	0	303	50	0	0	353	303	0
Silicic	69.20	0	0	346	0	0	346	0	0
Silicic	69.35	0	232	92	1	0	325	232	1
Silicic	71.00	413	80	2	0	0	495	493	0
Silicic	73.22	359	0	4	0	0	363	359	0
Silicic	74.80	486	0	0	0	0	486	486	0
Silicic	75.47	332	22	0	2	74	430	354	76
Silicic	75.66	458	7	0	0	0	465	465	0
Silicic	76.59	481	2	0	0	6	489	483	6
Silicic	76.79	468	20	0	0	0	488	488	0
Silicic	76.88	230	256	17	1	0	504	486	1
Silicic	76.93	313	37	107	0	0	457	350	0

dominated by Lvml, but with some Lvvg and Lvs. Silicic volcanic rocks tend to have end-member compositions, with examples of close to 100% of one component at each corner of the triangular plot. None of the studied samples contains significant quantities of all three components.

Although this data set is not as complete as it could be, it is hard to imagine that the quasi-random sampling of locations and volcanic rock types are so skewed as to make this data set an outlier to an overall, yet-to-be proven trend of clear, quantified relationships between volcanic lithic fragment types and silica composition. Even though there are slight differences between the way lithic fragments are categorized in this study and previous studies, it would be a leap of logic that these slight differences in definitions of lithic-fragment types would create a data set significantly different from a comparable data set using Dickinson's (1970) less quantitative definitions.

TABLE 2.—Classification matrix (cases in row categories classified into columns).

	Mafic	Intermediate	Silicic	%Correct
Mafic	19	0	0	100
Intermediate	3	48	0	94
Silicic	6	3	15	63
TOTAL	28	51	15	87

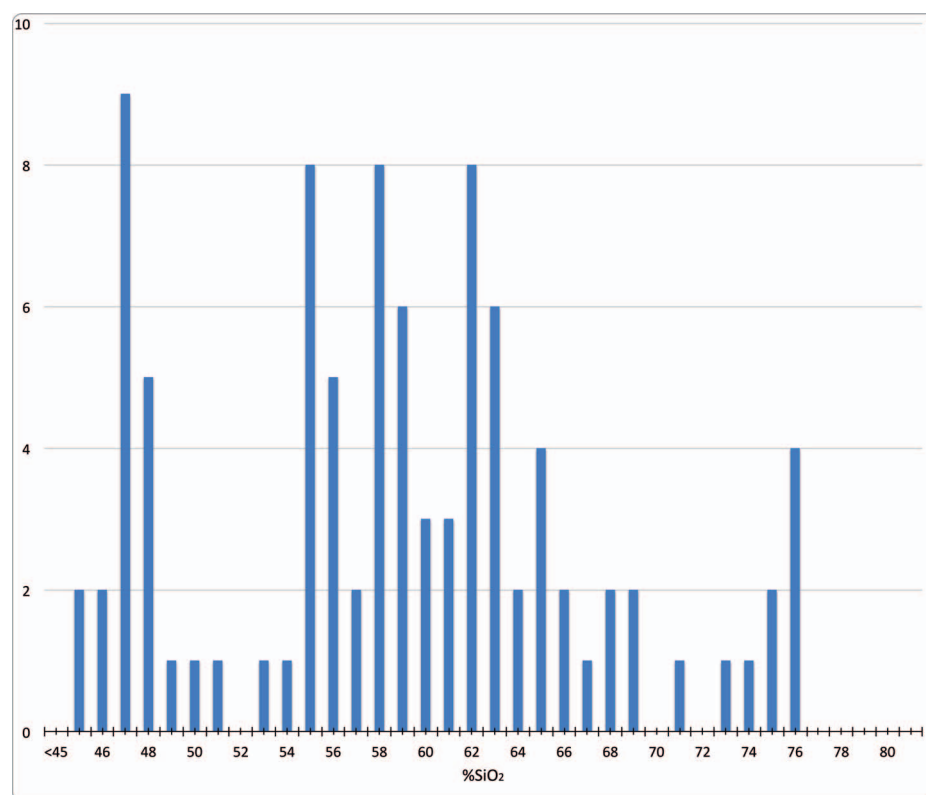


FIG. 3.—Histogram showing number of samples versus %SiO₂.

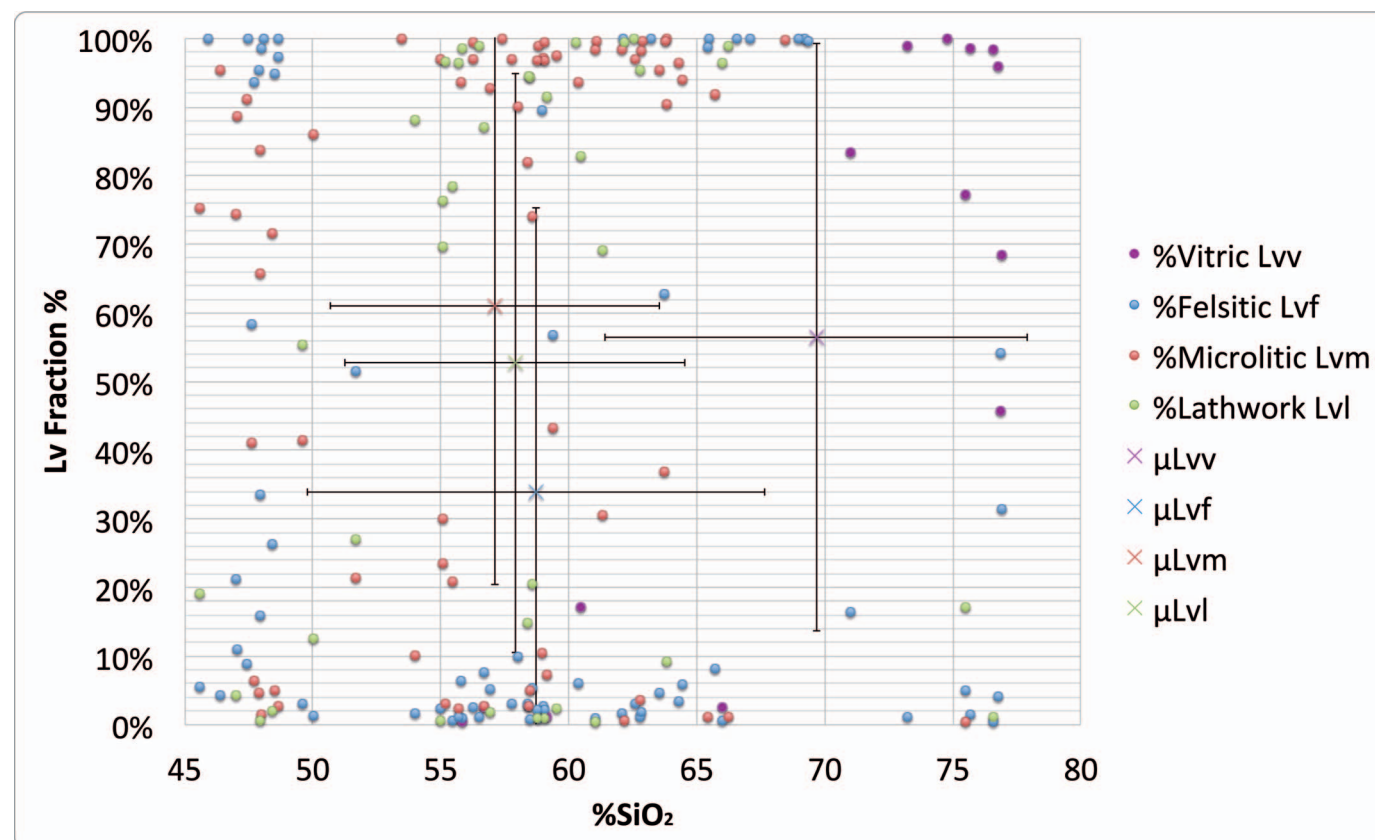


FIG. 4.—Proportions of four primary volcanic lithic types (e.g., Dickinson 1970) versus %SiO₂. Also shown are means and standard deviations for each type. Zero values are excluded. Vitric volcanic lithics are more commonly associated with silicic volcanics; the other three lithic types are highly variable.

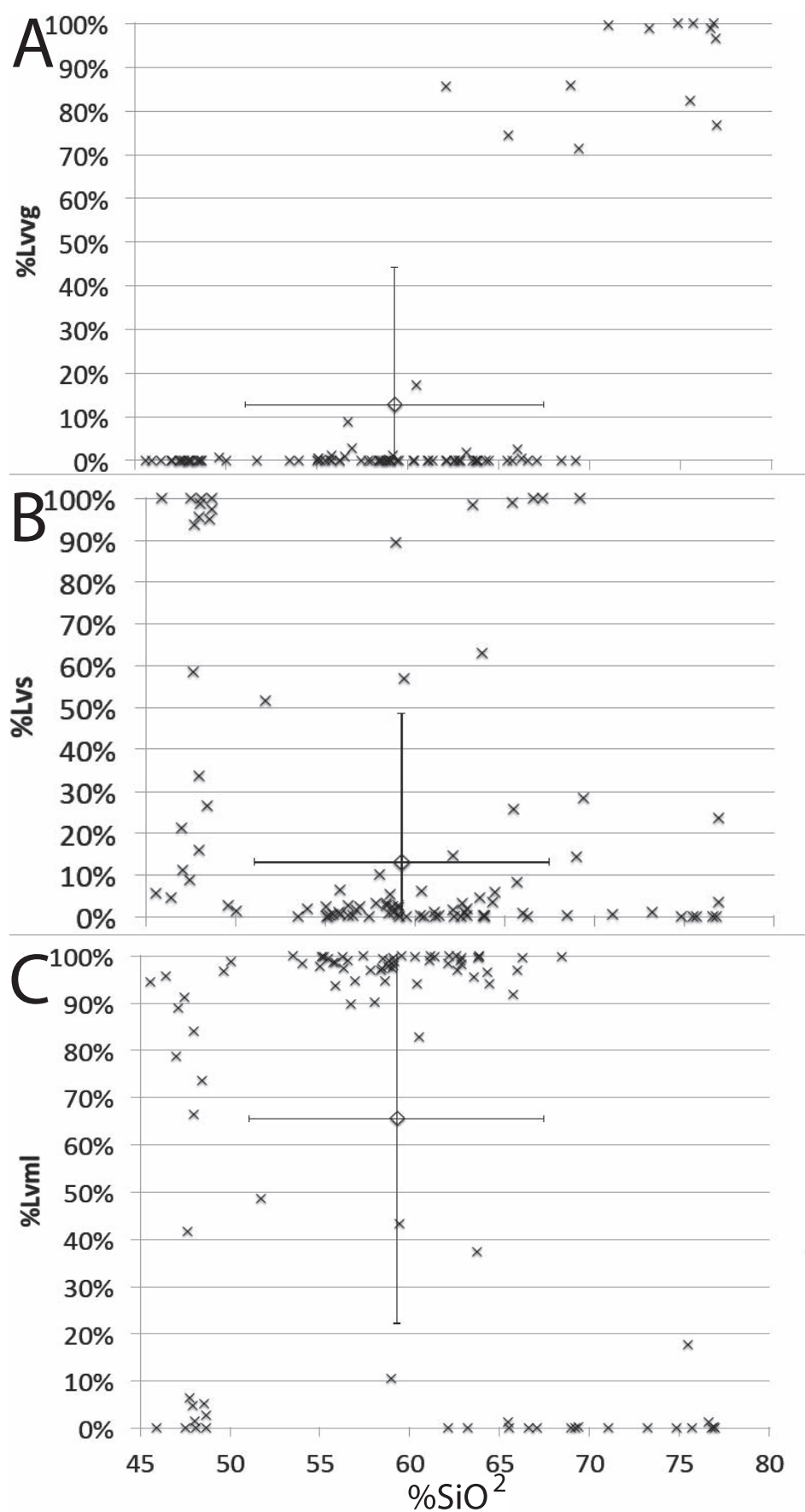


FIG. 5.—Proportions of volcanic lithic types (as grouped by discriminant analysis) versus SiO_2 . **A)** Vitric and granular volcanic lithics (Lvvg); **B)** seriate volcanic lithics (Lvs); **C)** microlitic and lathwork volcanic lithics (Lvml). Note that highest values for Lvvg correlate with high SiO_2 ; highest values of Lvs correlate with low SiO_2 ; and highest values for Lvml correlate with intermediate SiO_2 .

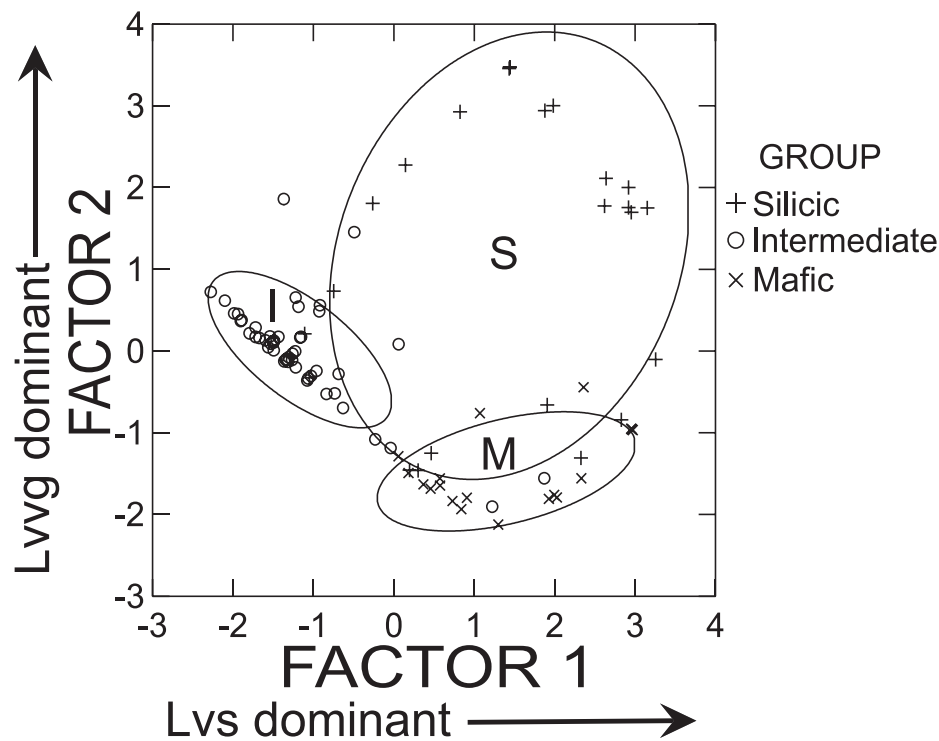


FIG. 6.—Canonical-scores (factors) plot using three variables (Lvvg, Lvs, Lvml) to define three groups (S, I, M). Plot shows plane of maximum separation of three groups, based on two factors. Factor 1 is dominated by positive Lvs and negative Lvml; Factor 2 is dominated by positive Lvvg and negative Lvs.

CONCLUSIONS

Based on the data gathered in this study, it is not recommended that the presence of specific volcanic lithic fragments be used to determine volcanic source-rock composition. While some samples do provide a match to the original definitions and correlations as established by Dickinson (1970), many samples do not. This conclusion is based on the observation that specific volcanic lithic fragments are found in samples of many different compositions, and specific compositions produce diverse volcanic lithic-fragment types. The only definitive conclusion is that samples containing dominantly vitric and granular volcanic lithic fragments can be confidently assigned to high-SiO₂ sources. More tentative conclusions are that mafic volcanics have lithic types anywhere on the Lvs–Lvm–Lvl spectrum, and that intermediate volcanics dominantly consist of Lvm and Lvl textures.

The conclusions of this study apply to zero-order samples (volcanic rocks). Extrapolating the results to the study of modern sand and ancient sandstone must consider relative preservation potentials of textural and compositional types. For example, vitric textures are the most reactive because they consist of glass, and they are fragile, especially as glass shards and bubble walls. On the other hand, high-SiO₂ compositions are generally more stable during weathering (e.g., Goldich 1938). As discussed by Ingersoll et al. (1993), silicic and intermediate volcanic components overwhelm mafic volcanic components in the modern sand of the Rio Grande rift of Colorado and New Mexico. This is just one example of how sand/sandstone composition is modified during weathering, transport, and deposition in first-, second- and third-order drainage systems. Nonetheless, the present study demonstrates the usefulness of studying zero-order samples using the Gazzi-Dickinson point-counting method so that initial components of the sedimentary system can be quantified.

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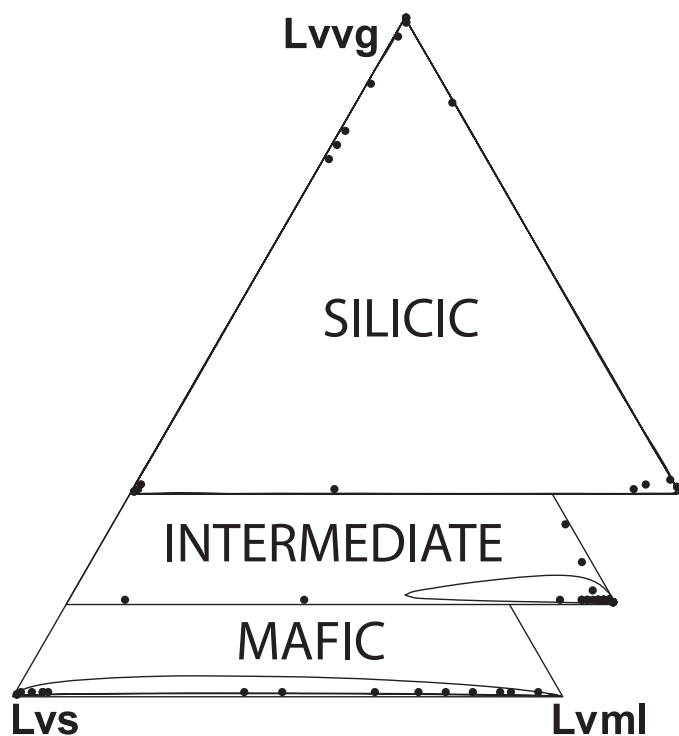


FIG. 7.—Ternary plots (Lvvg–Lvs–Lvml) of three petrofacies, including 95% confidence regions for geometric means (Weltje 2002). The confidence region for the silicic plot includes the entire triangle. See text for discussion.

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