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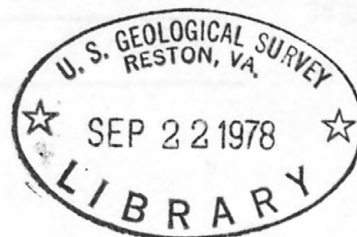UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY . [Reports-Open file series]

Comparison of the Wilfley Concentration Table
and Hand Panning for Concentration of
Heavy Minerals Prior to Geochemical Analysis

by

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This report is preliminary and has not been
edited or reviewed for conformity with U.S.
Geological Survey standards and nomenclature.

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Introductory Statement

Chemical analysis of heavy-mineral concentrates of stream sediments is a common geochemical exploration technique used by the U.S. Geological Survey. Generally these concentrates are prepared by hand panning at streamside or in a washtub and then further concentrated using heavy-liquid (bromoform) techniques in a laboratory. Concentration using heavy liquids is slow, tedious, and expensive for large surveys such as mineral evaluation of wilderness areas. In addition the cost of bromoform is expected to increase greatly because most if not all chemical companies in the United States have ceased production of the compound due to problems in meeting the safety standards of the U.S. Environmental Protection Agency (E.P.A.). Preliminary studies by the E.P.A. suggest a severe health hazard may be incurred by inhaling vapors of or contacting the skin with chemicals like bromoform. Heavy-liquid concentration of thousands of heavy-mineral samples carries an unavoidable risk of exposure to bromoform. The risk, expense, and time required by routine heavy-liquid concentration of heavy minerals should be eliminated by finding other methods to satisfactorily concentrate minerals whenever it is possible.

Heavy-mineral concentrates can be used in several ways in geochemical exploration and each way has certain standards for the nature and quality of the mineral concentration required. The nature of the concentration refers to whether the heavy minerals are analyzed in bulk or whether they are split into magnetic fractions using a hand

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magnet and possibly a Frantz Isodynamic Magnetic Separator[1]. The

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[1]The use of a brand name is for descriptive purposes and does not necessarily constitute endorsement by the U.S. Geological Survey.

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quality of the concentrate refers to the perfection of separation into the chosen mineral fractions. This quality can be expressed in weight percent dilution of one mineral class by minerals of other classes of the concentrate or by light minerals such as quartz and feldspar. The nature and quality of concentration required for a geochemical study depend on the comparisons to be made. Heavy-mineral concentrations may be made solely to bring the metal contained in the heavy minerals above the lower detection limits for the analytical equipment. Other uses include concentrating sulfide and oxide minerals for analysis, and concentrating individual minerals such as gold or platinum. Studies of rare but high value minerals such as gold require a high percent recovery of the mineral, Frantz separation may not be necessary, and dilution of as much as 50 percent light minerals probably is not a problem. On the other hand, heavy-mineral concentrates prepared for chemical analysis should have a low percent dilution by light minerals, the dilution should not vary greatly, the recovery need not be high as long as it completely represents the sample, remains approximately constant and involves no selective bias, and, magnetic separation may be desirable for some studies. A high percent of recovery of heavy minerals can usually be achieved at the cost of additional time and possibly higher dilution, but it may be unnecessary if the required

geochemical data can be obtained at lower percent recovery. Furthermore, high density minerals (specific gravity (S.G.) > 4.5), such as most sulfides and many oxides are recovered with greater efficiency by density methods than are minerals in the S.G. range of 3.5 to 4.5 (Theobald, 1957, p. 7). Thus many of the minerals sought in geochemical surveys of stream sediments such as molybdenite, scheelite, cassiterite, and chalcopyrite should be more completely recovered than less dense heavy minerals of perhaps less geochemical interest such as kyanite, sillimanite, olivine, garnet, pyroxene, and hornblende. As such, a low to moderate percent recovery of total heavy minerals may be acceptable for some geochemical surveys.

This experiment seeks to find a one-step heavy-mineral concentrating technique that can be used in reconnaissance geochemical surveys of stream sediments over large regions. The method should be safe, economical, fast, and produce concentrates with adequate and reasonably consistent percent recovery and percent dilution.

Heavy-mineral concentrating techniques consist of the following five main types (Taggart, 1956, p. 11-01 to p. 11-140): (1) pulsated beds, including various types of jigs; (2) shaken beds, including gold pans, rockers, Wilfley and other tables, and vanners; (3) stirred beds, including sluices, diamond pans, suspensoid media, and heavy liquids; (4) water-impulse separators, such as film sizing and classifier separators; and (5) pneumatic concentration, such as pneumatic quicksand and blowing. These techniques separate minerals of different specific gravities in response to gravity in combination with one or more other forces. Usually the downward penetration of the minerals induced by the

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force of gravity is resisted by the density and viscosity of a fluid such as water. The fluid moves at about a 90° angle to the force of gravity in some techniques that use friction between the minerals and a solid supporting surface to assist in the separation.

These mineral concentrating techniques are variously affected by grain size and shape as well as specific gravity. In general, wide ranges of size and shape deter effective separation according to specific gravity; thus some sieving to narrow the size range of stream sediments may be necessary prior to concentration. However, speed and economy are promoted by using concentration methods that are less sensitive to grain-size and shape effects.

For effective separation of heavy minerals with a Wilfley table, the size range of the minerals grains must be large enough to permit reverse size classification (coarse grains over finer grains) but not so large a range that the water flow necessary to scour out tailings on the unriffled part of the table carries heavy minerals downslope into the middlings pan. The effective size range for the Wilfley table as well as pan and jig increases with the concentration criterion (C), which is the ratio $\frac{SH-R}{SL-R}$, where SH = density of heavy mineral, SL = density of a light mineral, and R = density of the liquid. (Taggart, 1956, p. 11-02). A corollary is that for any given size range the denser heavy minerals will be more effectively concentrated than the less dense heavy minerals. Ore milling experience indicates that separation according to mineral density is not commercially possible for C < 1.25 (Taggart, 1956, p. 11-02). Thus, if water be the fluid, minerals with specific gravities less than about 3.1 cannot be effectively separated from

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quartz in large volume density concentration operations. Taggart (1956, p. 11-02) indicates that separation of minerals by density is easy, even to the finest sand sizes where the concentration criterion is greater than 2.5 (that is, quartz at S.G. of 2.65 and minerals $\geq$ S.G. of 5.1). Quartz and minerals as dense as S.G. of 3.9 can be commercially separated down to a grain size of about 150 μm. Thus, effective separation of minerals less dense than 3.9, including some sphalerite, siderite, limonite, psilomelane, secondary copper minerals, aluminum silicates such as sillimanite, pyroxene, hornblende, biotite, fluorite, apatite, tourmaline, epidote, and allanite probably cannot be completely achieved in large volume operations from quartz at grain sizes as fine as 150 μm. Percent recovery of medium density minerals such as these should vary directly with median grain size of the minerals to be separated.

Of the methods described by Taggart (1956), the gold pan, fine jig, and Wilfley table appear to be most suited for rapidly concentrating heavy minerals in small samples of stream sediments. A comparison of the Wilfley table with a fine jig reported by Taggart (1956, p. 11-70) showed that the Wilfley table had twice the capacity of the jig, made a higher recovery, and required less-skilled labor, less water, less power, and less repairs. Furthermore, the table makes a slime (fine particle) separation not made by the jig. The jig concentrates had less dilution than the Wilfley concentrations in that test. An additional factor important for the present experiment is that jigs are harder to clean than the table, thereby allowing more chance for contamination of samples. The gold pan has many of the advantages of the Wilfley table

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and of course is simpler and cheaper. In the hands of an expert, the gold pan produces heavy-mineral concentrates with as little as one percent dilution by light minerals (Theobald, 1957, p. 47, Sample T). A major disadvantage of the gold pan is the difficulty of standardizing the technique so that consistent recovery and dilution of the concentrate by light minerals can be achieved.

The gold pan and the Wilfley table appear the best readily available concentration methods for use in geochemical surveys. Therefore this experiment compares heavy-mineral concentrates prepared by these methods with concentrates prepared from splits of the same samples prepared using heavy-liquid techniques. Data from an extensive experiment in the use of the gold pan by Theobald (1957) will be compared to data obtained in this experiment.

Method of Experiment

Five samples of about 5 kg each of active stream sediment from Clear Creek near Blackhawk, Colorado, were divided into two parts--one part to be concentrated by hand panning and the other to be concentrated using the Wilfley table. Figure 1 shows a flow sheet for these subsamples. The grain-size distribution by weight percent of the subsamples concentrated on the Wilfley table is shown in figure 2.

The size distributions of the samples are slightly to moderately skewed toward finer sediments. Four of the samples have median sizes ranging from about 0.2ϕ (1.15 mm) to 0.9ϕ (1.90 mm) in the very coarse sand range, where ϕ is a logarithmic transformation of the Wentworth grand scale for sediment (Griffiths, 1967, p. 75). Sample J has a median size of 1.25ϕ (421 µm) in the medium-grained sand range.

Panning

Methods of panning are excellently discussed by Theobald (1957) and the theory of the technique is discussed by Taggart (1956). In this experiment, one geologist (S.D.L.) who had several years of experience in panning samples for geochemical analysis, produced the five panned concentrations in about two hours (slightly more than 20 minutes per sample). Greater variation could be expected if several operators having a large range of experience were involved in panning.

Wilfley Table

Use of the Wilfley table is thoroughly discussed by Taggart (1956). In this experiment a side slope of the table of 31 cm/m, a water flow of 7.2 L/min., and a moderately slow oscillation speed appeared to produce the optimum concentration of small samples (about one liter in volume)
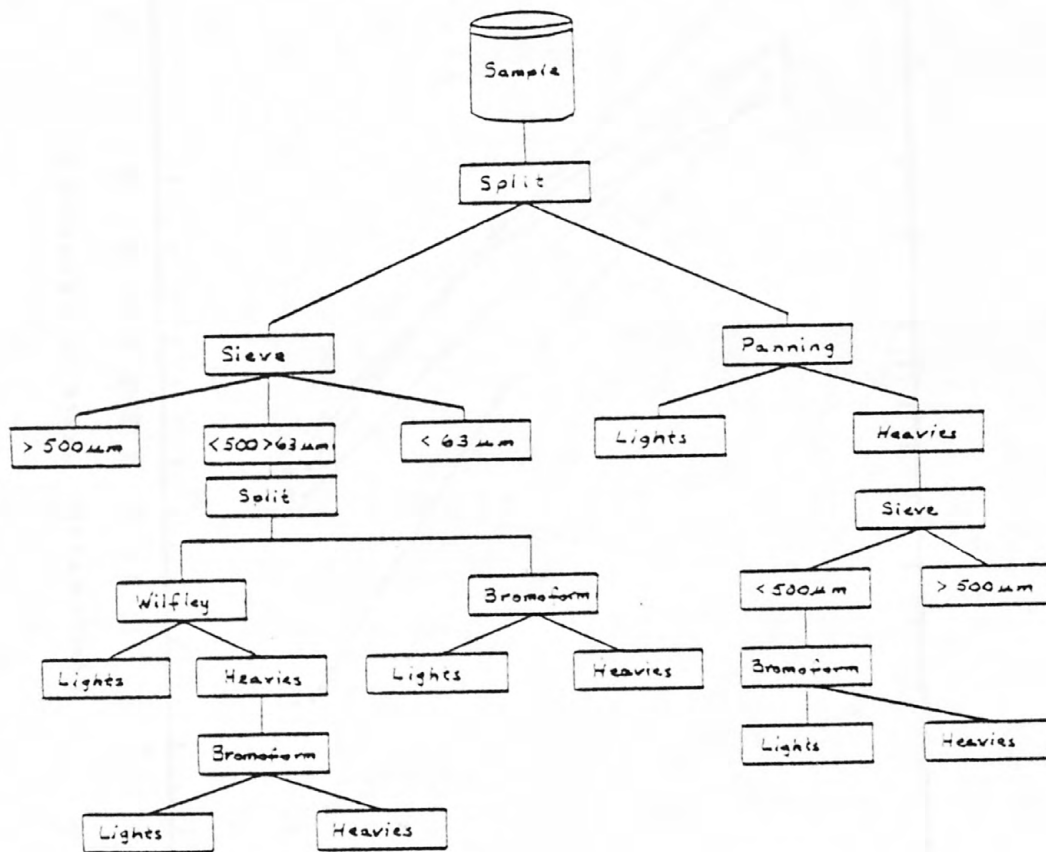
Figure 1. Flow sheet for comparison of Wilfley Concentrating Table with hand panning
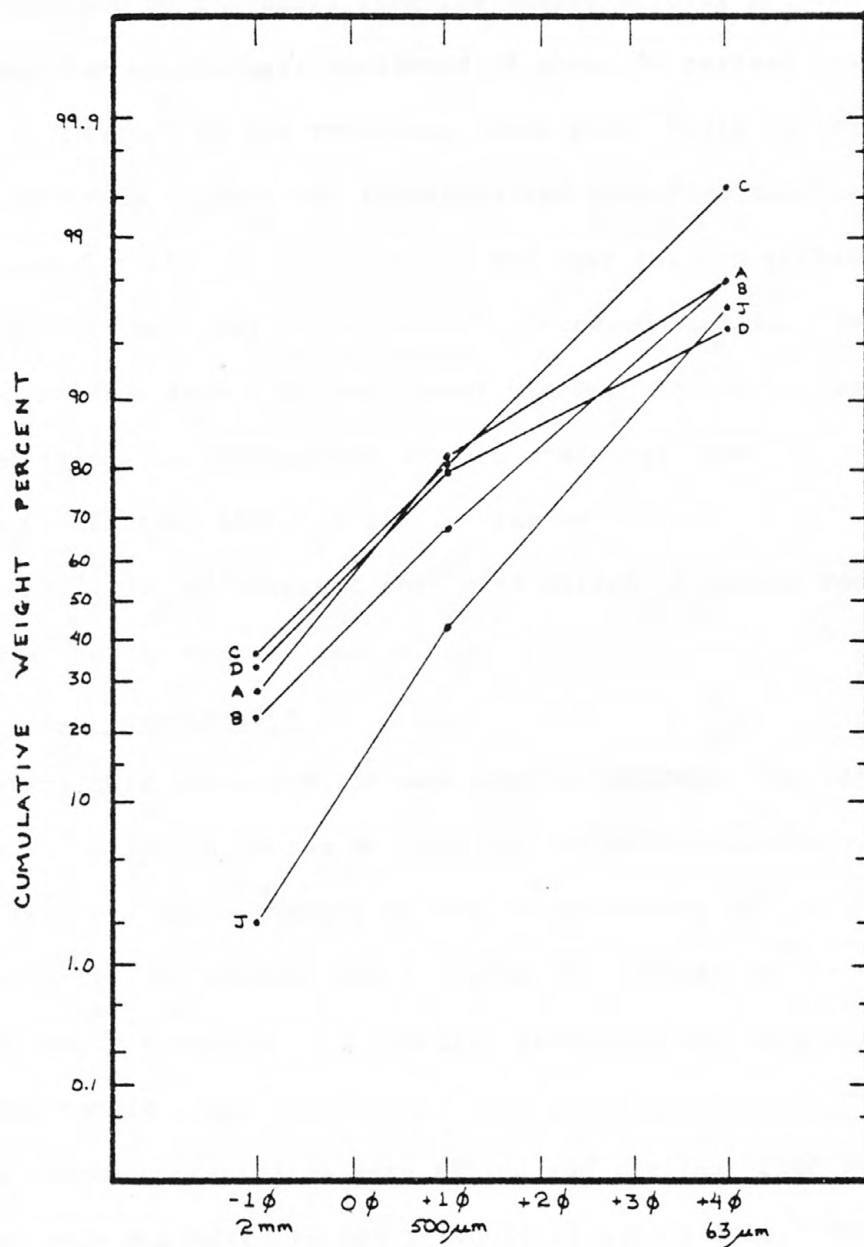
FIGURE 2: CUMULATIVE FREQUENCY DISTRIBUTIONS OF STREAM SEDIMENT SAMPLES (A-D, J) FROM CLEAR CREEK, NEAR BLACKHAWK, COLORADO, ON ARITHMETIC-PROBABILITY GRAPH PAPER.

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processed only once across the table. Concentrates were collected in the farthest pan on the table from the sample loading point. Material in the next pan (middlings) consisted of about 50 percent heavy minerals. Material in the remaining three pans (tails) consisted mostly of light minerals (quartz and feldspar) and very fine material (slimes).

A sieve fraction of 500 to 63 μm was used for concentration on the table. Coarser material is not easily processed with fine sand and silt, and studies show that most heavy minerals in sedimentary rocks are contained in the medium-grained sand to coarse-grained silt (500-30 μm) fraction (Griffiths, 1967, p. 209). Uranium data reported by Wenrich-Verbeek (1977, p. 349) suggest that most zircon in stream sediments analyzed by her is coarser than 90 μm.

Heavy-liquid Concentration

Heavy-liquid concentration was used to determine the percent light minerals, or dilution in the Wilfley and panned concentrates. The percent recovery was estimated by comparison of the weight of heavy minerals in the concentrate per 100 grams of initial sample to the weight of heavy minerals in a straight bromoform separate per 100 grams of initial sample (fig. 1).

The panned concentrates were sieved and the less than 500 μm size fractions were subjected to heavy-liquid concentrations. This sieve separation was done to allow comparison with the concentrate prepared using only heavy-liquid techniques on a less than 500 μm size fraction.

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Results of Experiment

The percent dilution and recovery for each technique are shown in table 1 for the five samples, A-D and J.

Table 1.--Percent dilution and recovery of heavy minerals concentrated from the stream sediments by a Wilfley table and hand panning

Sample	Wilfley		Hand panning	
	percent dilution	percent recovery	percent dilution	percent recovery
A	7.2	31	43	29
B	1.3	40	46	38
C	1.2	36	43	46
D	3.1	36	33	53
J	7.9	11	57	17
Mean of samples ------	4.1	30.8	44	36.6
Variance of samples ------	8.3	106	59	160

Summary of Panning Experiment by Theobald

Theobald (1957) reports an extensive experiment on the use of the gold pan as a quantitative geologic tool. He describes the recovery of heavy minerals by mineral species (determined by grain counts of weighed concentrates) in panning and successive repanning of 26 stream sediment samples. The recovery in weights of individual heavy minerals at any point in the panning of a sample is compared to the total weight of individual heavy minerals recovered by all pannings of the sample. The recovery of all heavy minerals and the dilution of the concentrates by quartz and feldspar are not listed by Theobald but can easily be computed from his table 8. The percent recovery of total heavy minerals and the percent dilution by light minerals in the first panning of Theobald's samples are shown in table 2 for comparison with the results of Wilfley and pan concentration in this experiment. It should be noted that the percent recovery values reported by Theobald are somewhat high because all heavy minerals were not accounted for in his samples, especially where the samples were panned as few as four times. The panning experience of the several operators ranged widely in Theobald's experiment which was conducted over an 8-month field season under field conditions. Variation in recovery rates between samples processed by single operators at a single time was so large that no systematic differences between operator, or within operators, over the season could be proved (Theobald, 1957, p. 19).

Table 2.--The weight percent dilution by light minerals and weight
percent of total minerals recovered in the first panning of 26 samples
(Computed from data by Theobald (1957, table 8))

Sample	Percent dilution	Percent recovery	Sample	Percent dilution	Percent recovery
A	23	73	N	14	63
B	21	70	O	15	74
C	5	73	P	12	53
D	16	73	Q	3	46
E	4	71	R	20	45
F	7	63	S	16	59
G	14	70	T	1	43
H	13	60	U	10	45
I	22	59	V	12	38
J	26	74	W	14	42
K	22	69	X	15	34
L	14	50	Y	28	30
M	39	55	Z	41	47

Mean of total samples ----------------------	16	57
Variance of total samples ----------------------	92	182

Evaluation of the Data

Separate comparisons of percent recovery and percent dilution were made by an analysis-of-variance. Table 3 shows an analysis-of-variance of percent recovery for Wilfley table and hand-panned concentrates prepared by this experiment and by Theobald. The mean values of percent recovery for these two techniques as performed in this experiment do not differ more than would be expected by chance in one out of twenty experiments (95 percent confidence level). Theobald's data show a significantly higher recovery rate, which may result from his use of the concentrates to study placer deposits rather than as preparation for chemical analysis. Comparison of the variances of percent recovery of the two techniques for all data (table 2) indicates no significant difference in variation in recovery at the 95 percent confidence level.

Table 4 shows an analysis-of-variance of percent dilution of the concentrate by light minerals for Wilfley table and hand-panned concentrates. The mean values of percent dilution for the two sets of data for panned concentrates are 4 and 10 times the means of dilution for the Wilfley table. These differences are significant at the 95 percent confidence level. Furthermore, the variance of percent dilution for both sets of hand-panning data exceed that for the Wilfley table. This difference is also significant at the 95 percent confidence interval. Thus, hand panning produces a greater percent dilution than the Wilfley table and one that is much more variable.

Table 3.--<u>Analysis of variance of percent of total heavy minerals</u>

<u>recovered by use of the Wilfley table and hand panning</u>

[Chemical values were transformed to natural logarithms prior to analysis.
Pooled error-mean-square was used to test the main effects where sample
x treatment interaction was not significant. Error-mean-square was used
to test sample effects and the interaction-mean-square to test treatment
effects where the interaction was significant. All effects are compared
with tabled F values at the 95 percent confidence level and, the
appropriate degrees-of-freedom in Steel and Torrie (1960, table A-6).
Symbol d.f. designates degrees of freedom; n.s. indicates not statistically
significant; * indicates statistically significant; SS indicates sum of
squares; MS indicates mean square; F is a ratio of the mean square of
some effect to the appropriate error-mean-square; $F_{x,y}^{.05}$ designates a
tabled F value at the 95 percent confidence level for x degrees of freedom
in the numerator and y degrees of freedom in the denominator; and p
designates range of ranked means where 2 indicates adjacent means and 3
indicates means separated by one other mean]

Processing treatment	r_i	$\sum_j X_{ij}$	$\bar{X}_{i.}$	$\sum_j X^2_{ij}$	$\sum X^2_{i.}/r_i$	$\sum_j X^2_{ij}$
Theobald's panning -----	26	1479	57	88863	84132	4731
Wilfley -----	5	154	30.3	5274	4743.2	530.8
Ludington's panning -----	5	183	36.6	7499	6698	801
Totals -----	36	1816	124.4	101636	95573.2	6062.8

Condensed table of analysis of variance

Source of variation	d.f.	SS	MS	F
Among treatments	2	3966.2	1983.1	10.30*
Within treatments	33	6062.8	183.7	
Total	35	10029		

$$F_{2,30}^{0.05} = 3.32$$
(Steel and Torrie, 1960, table A.6)

$$CT = \frac{X^2_{..}}{\sum r_i} = \frac{(1816)^2}{36} = 91607$$

$$\text{Total SS} = \sum_{ij} X^2_{ij} - CT = 101636-91607 = 10029$$

$$\text{Treatment SS} = \sum_i \frac{X^2_{i.}}{r_i} - CT = 95573-91607 = 3966$$

$$\text{Error SS} = \text{Total SS} - \text{Treatment SS} = 10029-3966 = 6063$$

Duncan's New Multiple Range Test
(Steel and Torrie, 1960, p. 108, 114, and table A.7)

Value of p	2	3
Studentized significant range - 95% confidence level	2.89	3.04
Intermediate least significant range	39.16	41.19
Least significant range; $r_1 = 5$, $r_2 = 36$	13.20	13.38
Least significant range; $r_1 = 5$, $r_2 = 5$	17.50	18.41

Table 4.--<u>Analysis of variance of percent dilution of heavy minerals</u>

<u>in concentrates prepared using the Wilfley table and hand panning</u>

[Chemical values were transformed to natural logarithms prior to analysis.
Pooled error-mean-square was used to test the main effects where sample
x treatment interaction was not significant. Error-mean-square was used
to test sample effects and the interaction-mean-square to test treatment
effects where the interaction was significant. All effects are compared
with tabled F values at the 95 percent confidence level and, the
appropriate degrees-of-freedom in Steel and Torrie (1960, table A-6).
Symbol d.f. designates degrees of freedom; n.s. indicates not statistically
significant; * indicates statistically significant; SS indicates sum of
squares; MS indicates mean square; F is a ratio of the mean square of
some effect to the appropriate error-mean-square; $F_{x,y}^{.05}$ designates a
tabled F value at the 95 percent confidence level for x degrees of freedom
in the numerator and y degrees of freedom in the denominator; and p
designates range of ranked means where 2 indicates adjacent means and 3
indicates means separated by one other mean]

	r_i	$\sum\limits_{j} X_{ij}$	$\bar{X}_{i.}$	$\sum\limits_{j} X_{ij}^2$	$X_{i.}^2/r_1$	$\sum\limits_{j} X_{ij}^2$
Theobald's panning -----	26	427	16	9403	7012.7	2390.3
Wilfley -----	5	20.7	4.1	126.99	85.7	41.29
Ludington's panning -----	5	222	44.4	10152	9857	295
Total -----	36	669.7	64.5	19681.99	16955.4	2726.59

Condensed table of analysis of variance

Source of variation	d.f.	SS	MS	F
Among treatments	2	4497.4	2248.7	27.13*
Within treatments	33	2735.59	82.9	
Total	35	7223.99		

$$F_{2,30}^{0.05} = 3.32$$
(Steel and Torrie, 1960, table A.6)

$$CT = \frac{X_{..}^2}{\Sigma r_i} = \frac{(669.7)^2}{36} = 12458$$

Total SS $= \sum\limits_{ij} X_{ij}^2 - CT$, $1968 - 12458 = 7223.99$

Treatment SS $= \sum\limits_{i} X_{i.}^2/r_i - CT$, $12955.4 - 12458 = 4497.4$

Error SS = Total SS - Treatment SS = 2735.59

Duncan's New Multiple Range Test
(Steel and Torrie, 1960, p. 108, 114, and table A.7)

Value of p	2	3
Studentized significant range - 95% confidence level	2.39	3.04
Intermediate least significant range	26.30	27.66
Least significant range; $r_1 = 5$, $r_2 = 26$	3.86	9.32
Least significant range; $r_1 = 5$, $r_2 = 5$	11.76	12.36

Evaluation of Possible Geochemical Bias Resulting from Variations

in Recovery of Heavy Minerals

In order to check for possible bias in variable recovery of
different heavy minerals by the Wilfley table and panning compared to
the bromoform concentrate, duplicate spectrographic analyses were made
of each of the 15 samples evaluated above. The samples were coded and
analyzed in random order.

Semiquantitative spectrographic analyses of the concentrates are
shown in table 5. The qualified data were assigned values according to
the following scheme: G, one spectrographic reporting unit higher than
the maximum value reported; L, one spectrographic reporting unit lower
than the minimum detectable value; and N, two spectrographic reporting
units lower than the minimum detectable value. The data were then
transformed into logarithms; and, samples and concentration treatments
were evaluated by two-way analysis-of-variance methods for each element
except for Mn, Co, Ni, and W, which generally are monotonously similar
for all samples. The treatments are fixed effects and the samples are
random, resulting in a mixed model for the analysis (Steel and Torrie,
1960, p. 134). Samples and treatment effects and the sample treatment
interaction were tested for significance by comparison with tabled
values for F at the 95 percent confidence level and the appropriate
number of degrees of freedom (table 6). Sample treatment interaction
was significant for Mg, Ca, Ba, and Mo, indicating that the treatments
produced different kinds of concentrates on different samples in terms
of these elements. The five samples have similar geometric means except
for Fe, Mg, V, and Zr. The concentration treatments showed significant

differences for all elements tested except Ti, Ba, Cr, Pb, and Za.
Detailed interpretation of these evaluations would require study of the
mineral residence for each element which is beyond the scope of this
paper; however, some suggestions may be made.

Table 5.--Analyses of heavy-mineral concentrates, samples A-D, and J

[Samples were analyzed by Donald A. Risoli using a six-step semiquantitative spectrographic method. N, not detected at sensitivity limit shown; L, detected, but lower than sensitivity limit shown; G, greater than value shown]

	Sample	Fe	Mg	Ca	Ti	Mn	Ag	B	Ba	Co	Cr	Cu	La
			Semiquantitative spectrographic analyses (percent)						(ppm)				
Wilfley	A-1	50	0.3	0.3	1	3,000	300	20	700	30	300	200	700
	A-2	50	0.5	0.3	1	5,000	1.5	L20	200	30	300	150	500
	B-1	G50	0.2	0.15	1.5	3,000	1	L20	700	30	300	150	500
	B-2	G50	0.15	0.15	1	3,000	L1	20	700	30	300	150	700
	C-1	G50	0.15	0.2	0.7	3,000	7	L20	500	30	300	150	700
	C-2	G50	0.15	0.15	1	3,000	15	L20	300	30	300	150	700
	D-1	50	0.15	0.15	0.7	5,000	1	20	300	30	300	300	700
	D-2	G50	0.15	0.15	0.7	3,000	L1	20	300	30	500	200	700
	J-1	50	0.15	0.15	1	3,000	L1	20	300	30	500	200	700
	J-2	50	0.15	0.15	1	3,000	N1	20	300	30	500	200	700
Panning	A-1	G50	1.5	1.5	1.5	3,000	15	50	200	30	300	300	500
	A-2	50	0.7	0.7	1	3,000	15	20	300	30	300	200	300
	B-1	G50	1.5	1.5	0.7	3,000	.15	L20	300	30	300	200	500
	B-2	G50	0.7	0.7	0.7	3,000	3	L20	150	30	500	150	300
	C-1	G50	1.5	1.5	1.5	3,000	7	20	300	50	700	700	300
	C-2	50	1.5	0.7	1.5	3,000	2	30	700	30	300	300	500
	D-1	G50	0.7	0.7	1	3,000	1.5	50	500	30	300	300	500
	D-2	G50	0.7	0.3	1.5	3,000	3	20	700	30	500	200	700
	J-1	30	1.5	0.7	1	3,000	70	50	700	30	300	300	700
	J-2	G50	1.5	1.5	1	3,000	7	50	700	30	500	300	1,000
Bromoform	A-1	30	3	2	1	3,000	7	50	700	30	300	300	700
	A-2	30	3	0.2	1	3,000	7	50	300	50	300	200	200
	B-1	30	2	1.5	1	3,000	1.5	70	300	30	300	200	500
	B-2	50	2	1.5	0.7	3,000	10	20	300	30	300	300	300
	C-1	50	3	1.5	1	5,000	3	100	300	50	300	300	300
	C-2	50	3	1.5	0.7	3,000	15	50	300	30	300	200	300
	D-1	50	2	1.5	1	5,000	3	70	300	50	300	300	300
	D-2	50	2	1.5	0.7	3,000	50	20	300	50	300	300	500
	J-1	30	3	1.5	0.7	3,000	3	50	700	30	300	300	300
	J-2	30	3	1.5	1.5	3,000	3	50	700	50	300	300	300

Table 5.--Analyses of heavy-mineral concentrates, samples A-D, and J--Continued

Semiquantitative spectrographic analyses
(ppm)

Sample		Mo	Ni	Pb	Sc	Sn	Sr	V	W	Y	Zn	Zr
Wilfley	A-1	10	70	150	15	100	N20	700	N100	700	1,500	1,000
	A-2	10	70	100	15	20	N20	500	N100	300	1,500	300
	B-1	15	70	100	15	30	N20	700	N100	300	1,500	1,000
	B-2	10	50	70	15	L20	N20	700	N100	300	2,000	500
	C-1	20	70	100	15	20	N20	500	L100	700	1,500	700
	C-2	15	70	70	15	20	N20	500	L100	700	2,000	2,000
	D-1	10	70	100	10	100	N20	500	N100	500	2,000	300
	D-2	15	70	70	15	70	N20	500	N100	500	1,500	500
	J-1	10	70	100	15	150	N20	500	150	700	1,500	1,500
	J-2	L10	70	150	15	L20	N20	500	N100	700	1,500	1,500
Panning	A-1	10	70	150	20	70	N20	500	N100	700	3,000	700
	A-2	15	70	150	15	N20	N20	500	L100	700	2,000	1,000
	B-1	15	70	150	30	20	L20	500	L100	300	1,500	2,000
	B-2	15	70	300	20	N20	N20	500	N100	500	1,000	2,000
	C-1	15	70	150	30	L20	N20	300	L100	700	1,500	1,500
	C-2	10	70	150	20	20	N20	500	N100	300	2,000	500
	D-1	15	70	150	20	N20	N20	500	N100	300	1,500	1,000
	D-2	15	70	150	20	70	N20	500	L100	300	1,500	1,000
	J-1	10	70	150	15	70	L20	300	N100	300	2,000	G2,000
	J-2	10	70	150	20	L20	L20	300	L100	500	1,500	G2,000
Bromoform	A-1	30	70	300	30	L20	L20	300	N100	200	3,000	300
	A-2	30	70	150	30	20	L20	500	N100	150	2,000	500
	B-1	20	70	150	30	50	N20	500	N100	300	2,000	700
	B-2	20	70	200	20	30	N20	500	N100	300	1,500	700
	C-1	15	70	150	30	30	L20	500	N100	200	3,000	500
	C-2	20	70	200	30	50	L20	500	N100	300	1,500	300
	D-1	20	70	300	30	20	L20	500	L100	300	2,000	700
	D-2	15	70	200	30	L20	N20	500	N100	200	3,000	500
	J-1	20	70	200	30	L20	L20	300	L100	300	2,000	1,000
	J-2	15	100	300	30	20	N20	500	N100	200	3,000	1,500

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Table 6.--<u>Two-way analysis-of-variance for chemical analyses</u>

<u>of heavy-mineral concentrates</u>

[Chemical values were transformed to natural logarithms prior to analysis. Pooled error-mean-square was used to test the main effects where sample x treatment interaction was not significant. Error-mean-square was used to test sample effects and the interaction-mean-square to test treatment effects where the interaction was significant. All effects are compared with tabled F values at the 95 percent confidence level and, the appropriate degrees-of-freedom in Steel and Torrie (1960, table A-6). Symbol d.f. designates degrees of freedom; n.s. indicates not statistically significant; * indicates statistically significant; SS indicates sum of squares; MS indicates mean square; F is a ratio of the mean square of some effect to the appropriate error-mean-square; and $F_{x,y}^{.05}$ designates a tabled F value at the 95 percent confidence level for x degrees of freedom in the numerator and y degrees of freedom in the denominator]

Table 6.--Two-way analysis-of-variance for chemical analyses
of heavy-mineral concentrates--Continued

Fe

Source of variation	d.f.	SS	MS	F	Tabled F
Sample	4	0.741	0.185	4.695*	$F_{4,23}^{.05} = 2.80$
Treatment	2	1.243	0.622	15.787*	$F_{2,23}^{.05} = 3.42$
Sample x Treatment	8	0.248	0.031	0.706*	$F_{8,15}^{.05} = 2.64$
Error	15	0.659	0.0439		
Pooled Error	23	0.907	0.0394		
Total	20	2.891			

Mg

Source of variation	d.f.	SS	MS	F	Tabled F
Sample	4	1.250	0.313	16.622*	$F_{4,15}^{.05} = 3.06$
Treatment	2	35.741	17.8705	109.10*	$F_{2,8}^{.05} = 4.46$
Sample x Treatment	8	1.310	0.1638	8.713*	$F_{8,15}^{.05} = 2.64$
Error	15	0.282	0.0188		
Total	29	38.583			

Table 6.--Two-way analysis-of-variance for chemical analyses

of heavy-mineral concentrates--Continued

Ca					
Source of variation	d.f.	SS	MS	F	Tabled F
Sample	4	0.100	0.025	1.316n.s.	$F_{4,15}^{.05} = 3.06$
Treatment	2	23.992	11.996	47.793*	$F_{2,8}^{.05} = 4.46$
Sample x Treatment	8	2.009	0.251	13.211*	$F_{8,15}^{.05} = 2.64$
Error	15	0.288	0.019		
Total	29	26.389			

Ti					
Source of variation	d.f.	SS	MS	F	Tabled F
Sample	4	0.157	0.0393	0.518n.s.	$F_{4,23}^{.05} = 2.80$
Treatment	2	0.211	0.106	1.398n.s.	$F_{2,23}^{.05} = 3.42$
Sample x Treatment	8	0.952	0.119	2.258n.s.	$F_{8,15}^{.05} = 2.64$
Error	15	0.791	0.0527		
Pooled Error	23	1.743	0.0758		
Total	29	2.111			

Table 6.--<u>Two-way analysis-of-variance for chemical analyses</u>

<u>of heavy-mineral concentrates</u>--Continued

B

Source of variation	d.f.	SS	MS	F	Tabled F
Sample	4	0.919	0.230	1.285n.s.	$F_{4,23}^{.05} = 2.80$
Treatment	2	4.851	2.426	13.553*	$F_{2,23}^{.05} = 3.42$
Sample x Treatment	8	1.297	0.162	0.866n.s.	$F_{8,15}^{.05} = 2.64$
Error	15	2.812	0.187		
Pooled Error	23	4.109	0.179		
Total	29	9.878			

Ba

Source of variation	d.f.	SS	MS	F	Tabled F
Sample	4	1.050	0.263	1.963n.s.	$F_{4,15}^{.05} = 3.06$
Treatment	2	0.003	0.002	.005n.s.	$F_{2,8}^{.05} = 4.46$
Sample x Treatment	8	3.315	0.414	3.090*	$F_{8,15}^{.05} = 2.64$
Error	15	2.011	0.134		
Total	29	6.379			

Table 6.--Two-way analysis-of-variance for chemical analyses

of heavy-mineral concentrates--Continued

Cr					
Source of variation	d.f.	SS	MS	F	Tabled F
Sample	4	0.207	0.052	0.791n.s.	$F_{4,23}^{.05} = 2.80$
Treatment	2	0.175	0.088	1.339n.s.	$F_{2,23}^{.05} = 3.42$
Sample x Treatment	8	0.499	0.062	0.925n.s.	$F_{8,15}^{.05} = 2.64$
Error	15	1.012	0.067		
Pooled Error	23	1.511	0.0657		
Total	29	1.893			

Cu					
Source of variation	d.f.	SS	MS	F	Tabled F
Sample	4	0.635	0.159	2.005n.s.	$F_{4,23}^{.05} = 2.80$
Treatment	2	0.930	0.465	5.864*	$F_{2,23}^{.05} = 3.42$
Sample x Treatment	8	0.965	0.121	2.123n.s.	$F_{8,15}^{.05} = 2.64$
Error	15	0.860	0.057		
Pooled Error	23	1.825	0.0793		
Total	29	3.390			

Table 6.--<u>Two-way analysis-of-variance for chemical analyses</u>

<u>of heavy-mineral concentrates</u>--Continued

La

Source of variation	d.f.	SS	MS	F	Tabled F
Sample	4	0.373	0.0933	0.864n.s.	$F_{4,23}^{.05}= 2.80$
Treatment	2	2.014	1.007	9.324*	$F_{2,23}^{.05}= 3.40$
Sample x Treatment	8	0.814	0.102	0.919n.s.	$F_{8,15}^{.05}= 2.64$
Error	15	1.670	0.111		
Pooled Error	23	2.484	0.108		
Total	29	4.871			

Mo

Source of variation	d.f.	SS	MS	F	Tabled F
Sample	4	0.151	0.0378	0.987n.s.	$F_{4,15}^{.05} = 3.06$
Treatment	2	1.354	0.677	6.387*	$F_{2,8}^{.05} = 4.46$
Sample x Treatment	8	0.845	0.106	2.768*	$F_{8,15}^{.05} = 2.64$
Error	15	0.575	0.0383		
Total	29	2.925			

Table 6.--<u>Two-way analysis-of-variance for chemical analyses</u>

		Pb			
Source of variation	d.f.	SS	MS	F	Tabled F
Sample	4	0.347	0.0868	0.152n.s.	$F_{4,23}^{.05}= 2.80$
Treatment	2	2.290	1.150	2.014n.s.	$F_{2,23}^{.05}= 3.40$
Sample x Treatment	8	0.452	0.0565	0.0669n.s.	$F_{8,15}^{.05}= 2.64$
Error	15	12.681	0.845		
Pooled Error	23	13.133	0.571		
Total	29	15.770			

		Sc			
Source of variation	d.f.	SS	MS	F	Tabled F
Sample	4	0.0718	0.0180	0.581n.s.	$F_{4,23}^{.05}= 2.80$
Treatment	2	2.401	1.201	38.742*	$F_{2,23}^{.05}= 3.40$
Sample x Treatment	8	0.325	0.0406	1.568n.s.	$F_{8,15}^{.05}= 2.64$
Error	15	0.388	0.0259		
Pooled Error	23	0.713	0.0310		
Total	29	3.186			

Table 6.--<u>Two-way analysis-of-variance for chemical analyses</u>

<u>of heavy-mineral concentrates</u>--Continued

Sn

Source of variation	d.f.	SS	MS	F	Tabled F
Sample	4	2.384	0.596	1.409n.s.	$F_{4,23}^{.05} = 2.80$
Treatment	2	5.850	2.925	6.915*	$F_{2,23}^{.05} = 3.42$
Sample x Treatment	8	1.682	0.210	0.326n.s.	$F_{8.15}^{.05} = 2.64$
Error	15	9.664	0.644		
Pooled Error	23	9.727	0.423		
Total	29	19.580			

V

Source of variation	d.f.	SS	MS	F	Tabled F
Sample	4	0.423	0.106	3.164*	$F_{4,23}^{.05} = 2.80$
Treatment	2	0.349	0.175	5.224*	$F_{2,23}^{.05} = 3.42$
Sample x Treatment	8	0.332	0.0415	1.388n.s.	$F_{8,15}^{.05} = 2.64$
Error	15	0.448	0.0299		
Pooled Error	23	0.770	0.0335		
Total	29	1.552			

Table 6.--Two-way analysis-of-variance for chemical analyses

of heavy-mineral concentrates--Continued

Y					
Source of variation	d.f.	SS	MS	F	Tabled F
Sample	4	0.343	0.0858	0.655n.s.	$F_{4,23}^{.05} = 2.80$
Treatment	2	3.160	1.580	12.061*	$F_{2,23}^{.05} = 3.42$
Sample x Treatment	8	1.744	0.218	2.580n.s.	$F_{8,15}^{.05} = 2.64$
Error	15	1.267	0.0845		
Pooled Error	23	3.011	0.131		
Total	29	6.514			

Zn					
Source of variation	d.f.	SS	MS	F	Tabled F
Sample	4	0.167	0.0418	0.0937n.s.	$F_{4,23}^{.05} = 2.80$
Treatment	2	0.687	0.344	0.771n.s.	$F_{2,23}^{.05} = 3.03$
Sample x Treatment	8	1.126	0.141	0.232n.s.	$F_{8,15}^{.05} = 2.64$
Error	15	9.124	0.608		
Pooled Error	23	10.250	0.446		
Total	29	11.194			

Table 6.--Two-way analysis-of-variance for chemical analyses

of heavy-mineral concentrates--Continued

		Zr			
Source of variation	d.f.	SS	MS	F	Tabled F
Sample	4	5.160	1.29	6.684*	$F_{4,23}^{.05} = 2.80$
Treatment	2	3.43	1.715	8.886*	$F_{2,23}^{.05} = 3.42$
Sample x Treatment	8	1.734	0.217	1.199n.s.	$F_{8,15}^{.05} = 2.64$
Error	15	2.712	0.181		
Pooled Error	23	4.446	0.193		
Total	29	13.036			

Table 7 compares the geometric means of selected elements for all samples by concentration treatment. Figure 3 is a plot of the log of the ratio of the Wilfley and panning averages to the bromoform data. Presumably the elements which show little contrast between treatments (vanadium, chromium, titanium, barium) reside chiefly in minerals which are concentrated equally well by all treatments, for example barite (S.G., 4.5) and magnetite-ulvospinel (S.G., 5.2-4.8). The elements showing enrichment in the Wilfley and panned treatments might reside in minerals having high densities and thus be preferentially concentrated panning and especially by the Wilfley table. Metals apparently showing this effect are tin in cassiterite (S.G., 7.0), yttrium and lanthanum in monazite (S.G., 5.0-5.3), and iron in pyrite (S.G., 4.9).

Two elements, magnesium and calcium, are much lower in the Wilfley concentrate than in panning and bromoform concentrates. It seems likely that magnesium resides chiefly in biotite (S.G., 2.7-3.3) and calcium in epidote (S.G., 3.4-3.5), minerals less well recovered by the Wilfley table. Boron also shows a strong depletion in the Wilfley concentrate; it probably resides in tourmaline (S.G., 3.0-3.2) also a poor mineral for Wilfley concentration. A possibly related suite of elements (scandium, lead, molybdenum, copper, and zinc) is moderately depleted in the Wilfley fraction and it seems most likely that these are found chiefly as trace constituents of biotite or as tiny accessory sulfide strains in clots of biotite. If the chalcophile metals were in the form of free sulfides, they should have been better concentrated by the Wilfley treatment because of the high densities of chalcopyrite

Table 7.--Comparison of geometric means by element for each

concentration treatment

[n.s. indicates not significant; * indicates significant]

| Element	Geometric Means				
	Wilfley	Panning	Bromoform	Overall	Treatment F
Fe	59	60	39	52	15.787*
Mg	0.19	1.12	2.55	0.8	109.10*
Ca	0.18	1.10	1.26	0.6	47.79*
Ti	0.9	1.1	0.9	1.0	1.398n.s.
B	17	28	48	29	13.553*
Ba	391	397	387	392	0.005n.s.
Cr	350	381	316	348	1.339n.s.
Cu	180	259	266	232	5.864*
La	654	492	347	482	9.324*
Mo	13	13	20	15	6.387*
Pb	97	161	186	143	2.014n.s.
Sc	14	20	29	20	38.742*
Sn	38	22	13	22	6.915*
V	553	429	452	475	5.224*
Y	508	429	238	373	7.248*
Zn	1,635	1,584	2,216	1,790	2.440n.s.
Zr	768	1,342	597	851	7.030*
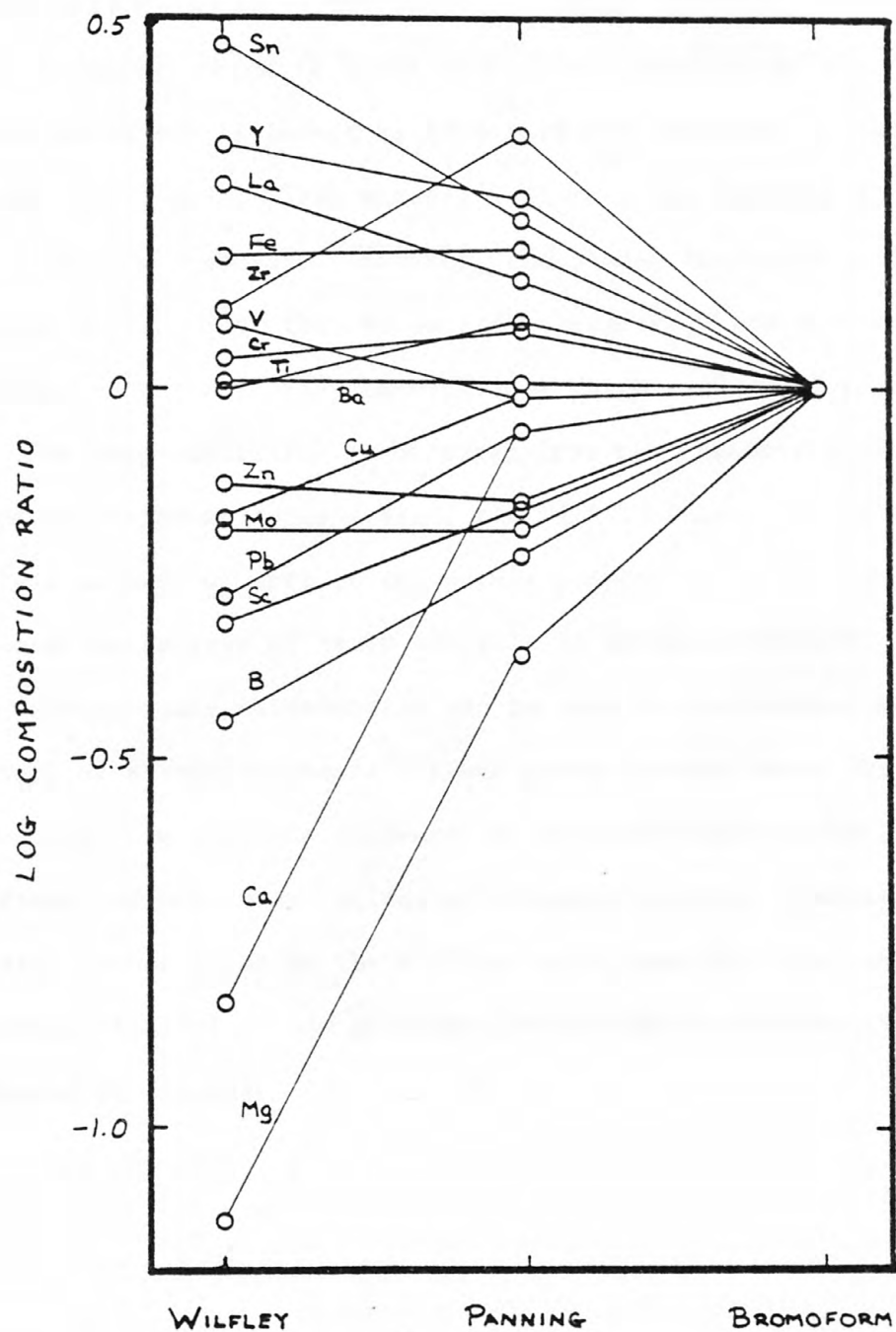
FIGURE 3: SCHEMATIC PLOT OF THE LOGARITHM OF THE RATIO:
AVERAGE COMPOSITION OF WILFLEY AND PANNED SAMPLES,
÷ AVERAGE COMPOSITION OF BROMOFORM SAMPLES.

(S.G., 4.2), molybdenite (S.G., 4.7), galena (S.G., 7.5), and sphalerite (S.G., 4.1).

Zirconium, which is lower in Wilfley concentrates than in panned concentrates and is lowest in bromoform concentrates, probably is in zircon (S.G., 4.7). This mineral is better concentrated by the Wilfley table than by bromoform. However, the panned concentrates probably include zircon finer than 63 μm and, therefore, have higher zirconium contents than the Wilfley concentrates which exclude these fine zircon.

The main conclusion to be drawn from the chemical data is that, compared to panned concentrates, the Wilfley concentrates are likely to contain as much or more of the metals commonly sought in geochemical exploration surveys of heavy minerals in stream sediments. Therefore, the Wilfley table concentrates can be used in geochemical exploration surveys of stream sediments without undue concern about detrimental bias resulting from variable recovery of different heavy minerals. In fact, sulfides and most heavy oxides of economic interest generally are more greatly concentrated by the Wilfley table than the other methods and the geochemical distribution patterns for the chalcophile metals should be enhanced by its use.

Conclusions

The relatively consistent low dilution by light minerals in concentrates prepared with the Wilfley table makes that equipment superior to the gold pan for one-step concentration of stream sediment heavy minerals for geochemical analysis. The one to seven percent (mean 4 percent) dilution of the Wilfley concentrates is so low that the difference between spectrographic analyses of these concentrates and of purer concentrates prepared by heavy-liquids techniques could not be significant, given the precision range (10-20 ppm; 100-200 ppm, and so forth) claimed for 65 percent of semiquantitative spectrographic analyses. This low precision of the spectrochemical technique most commonly used in geochemical surveys of stream sediments also suggests that magnetic separation could be done directly on the Wilfley concentrate without significantly increasing the variation of the chemical data. That is, if all 7 grams of quartz and feldspar in a 100 gram concentrate with 7 percent dilution were reconcentrated into a least magnetic fraction weighing 10 grams the dilution of that fraction would be 70 percent. Likewise, if all of one gram of similar light minerals in a 100 gram concentrate with 1 percent dilution were reconcentrated into a least magnetic fraction weighing 10 grams the dilution of that fraction would be 10 percent. The range of 60 percent dilution between these fractions would affect the chemical data but still is well within the precision of the chemical technique.

Chemical analysis of the concentrates prepared in this experiment shows no detrimental geochemical bias in the use of the Wilfley table as compared with the gold pan for geochemical surveys.

Although this experiment was made to evaluate the use of the Wilfley table for geochemical surveys of stream sediments, the data indicate that the technique probably can also be used to concentrate heavy minerals from crushed rock samples for petrographic study or chemical analysis. Partial recovery of intermediate density minerals and tabular minerals probably would not interfere with such studies of individual minerals.

Suggestions for Future Studies

Further study should be made of the effect of variations in grain-size distribution on dilution and recovery ratio of heavy minerals and to increase the percent recovery using small volume samples on the Wilfley table. The samples used in the present experiment ranged from medium- to very coarse grained sand (median diameter). The recovery rates achieved using the Wilfley table and hand panning were uniform and similar also for the very coarse sand samples. On the medium-grained sand (Sample J), however, both techniques recovered less than one third as much of the total heavy minerals as were recovered from the coarser samples. The percent dilution for both techniques also were slightly higher for Sample J than for the other samples in the experiment.

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