Using Sieving and Unknown Sand Samples for a Sedimentation-Stratigraphy Class Project With Linkage to Introductory Courses

Patricia E. Videtich[1,a] and William J. Neal[1]

ABSTRACT

Using sieving and sample "unknowns" for instructional grain-size analysis and interpretation of sands in undergraduate sedimentology courses has advantages over other techniques. Students (1) learn to calculate and use statistics; (2) visually observe differences in the grain-size fractions, thereby developing a sense of specific size ranges, weight percentages being plotted, and how grain composition and properties are a function of size; (3) are enthusiastic and observant as they search for clues of the origin of their sample, but discover that determining depositional environments using grain-size analysis is not the hoped for "fingerprinting" technique; and (4) enjoy learning the geographic origin and depositional environment of their sample. Plus, sieving equipment generally is less costly to acquire and maintain than "black box" techniques, and sieving is a commonly used procedure in industry. Using unknown sand samples results in some students making "incorrect" interpretations, which allows for illustrating that a scientist may have an excellent data set and a valid interpretation based on that data but, although the data are sound, the interpretation may be erroneous. Moreover, using a suite of unknowns allows students in a class to collectively be exposed to sands from a range of environments and geographic locales without the need for local sediment-rich environments. Building a set of unknowns is aided by recruiting students in introductory geology courses to collect and document samples during their school-break travels for future "unknowns," thereby linking courses and creating interest among nonmajors. When these students venture into the field to collect a sample and characterize the environment, they are enticed into thinking about sedimentary processes and possible anthropogenic effects, such as beach nourishment, while on break. © *2012 National Association of Geoscience Teachers*. [DOI: 10.5408/11-279.1]

Key words: size analysis, sieving, sand, statistics, textural parameters, provenance

INTRODUCTION

Sediment size analysis rightfully remains an essential laboratory exercise in undergraduate sedimentology courses. Beyond using sediment grain-size and textural parameters to describe sediments and sedimentary rocks, and performing fundamental tasks such as facies analysis (e.g., Barnhart et al., 2002), such basic data are also used to evaluate the economic potential of sediments and sedimentary rocks. In addition, standardized grain-size analysis techniques provide students with valuable skills that are used in sedimentology for a variety of other tasks including heavy mineral studies (e.g., Sawakuchi et al., 2009) and tectonic provenance determination (e.g., Ingersoll and Estmond, 2007), as well as in a variety of other disciplines including engineering geology (e.g., King and Gavin, 2002), glaciology (e.g., Hubbard et al., 2004), magnetics (e.g., Hatfield et al., 2010), and volcanology (e.g., Wohletz et al., 1989; Sarocchi et al., 2011). In addition to teaching students a useful skill, grain-size analysis exercises can help teach students the difference between obtaining a valid data set (their "results") that will stand the test of time, and their "interpretation" of that data set, which may be incorrect due to limitations of the data and the complexities of the natural world. This latter lesson is just as enlightening for the students as is obtaining the data set.

Received 13 December 2011; revised 23 May 2012; accepted 9 June 2012; published online 6 November 2012.

[1]Department of Geology, Grand Valley State University, Allendale, Michigan 49401 USA
[a]Author to whom correspondence should be addressed. Electronic mail: videticp@gvsu.edu.

Using sediment-size distributions to help define depositional settings is going into its third century of application, although experts concede "empirical understanding and modeling of sedimentary morphodynamic process-response systems through their particle-size distributions has remained an elusive problem to this day" (Hartmann and Flemming, 2007, p. 333). However, in the process of utilizing grain-size distributions to address questions in loose boundary hydraulics and sedimentology, analytical techniques have evolved that have a much wider application, as noted above. These techniques include physical description of industrial materials such as abrasives; fill; cover; filtering materials; glass, foundry, and fracking sands; and sands and gravels for construction materials (such as aggregate and cinder-blocks; Welland, 2009), as well as estimation of derived properties of sediments and sedimentary rocks (e.g., fluid reservoir characteristics such as porosity and permeability). The question arises as to what teaching approach may be best for developing student skills in both the straightforward technical approach to obtaining size-distribution data, and in interpreting and presenting the results.

Davies-Vollum (2006) summarizes the benefits of an upper-level sedimentation course using a multiweek, research-style, grain-size analysis project to develop field and laboratory skills with emphasis on bivariate plots of size parameters for interpreting the conditions of transport and deposition for subenvironments on a local beach. Davies-Vollum provides a good summary of the commonly determined size-distribution parameters, bivariate plots used, and the classic literature for interpretation of such plots (e.g., Passega, 1957; Friedman, 1967; Visher, 1969). Various techniques may be utilized for obtaining grain-size distributions of sands including the use of sieves, settling

TABLE I: Common size analysis techniques suitable for sand-sized sediments with notes in regards to pedagogy.

Size Analysis Technique	Advantages	Disadvantages	Comments
Sieving	easy-to-understand principles; individual size fractions retained for examination (petrography); can use for pebbles as well as sand	slow/labor intensive; no computer output	ideal for teaching principles of size distribution and composition; visual observation of size categories and grain properties possible
Laser diffraction particle size analyzer	fast sample processing; can be computerized to provide output (e.g., size distribution curves) to allow rapid calculation of size distribution statistics; can use for silt and clay as well as sand	individual size fractions not separated; no derived petrologic information; students less likely to recognize extraneous results	commercial units have higher initial costs and maintenance than sieving; "black box" methodology not as straightforward for understanding by students
Settling tube	same as particle analyzer except typically used for sand to coarse silt; provides visual aid in terms of understanding settling velocities	same as particle analyzer	requires more set-up and maintenance than sieving, and has higher initial cost

tubes, and laser diffraction (LD) particle size analyzers (Table I). The latter was used in the Davies-Vollum (2006) approach. Rodríguez and Uriarte (2009) discuss significant differences in results between the LD and dry sieving techniques, and provide a reference list of studies comparing LD and dry sieving methodologies.

The goal of this paper is to offer an approach for a grain-size analysis project as an alternative to that discussed by Davies-Vollum (2006). Similar to Davies-Vollum, the objective of our research-style, grain-size analysis project in Sedimentation-Stratigraphy (Sed-Strat, Geology 312) is to meet department goals and provide students with a number of benefits including (1) training in applied laboratory techniques; (2) practice using basic, standard statistical concepts (also recommended by Manduca et al., 2008); (3) generation of data sets that students interpret using some healthy skepticism regarding the scientific literature; and (4) practice writing a scientific report, taking care to separate results from interpretations. (See Appendix A for a more detailed correlation between our goals for the geology major, the exercise discussed herein, and a generalized grading rubric.)

We suggest that using a dry sieving exercise with unknown sand samples in which students not only calculate statistical parameters and construct a variety of plots, but also make visual observations of size fractions (Figs. 1 and 2) has a number of merits over other approaches, both practically and pedagogically (Table I). Indeed, Davies-Vollum (2006, p. 13) indicates that sieving can be used rather than LD "at no detriment to the project," but we suggest that, for teaching purposes, sieving has some advantages over the LD method. In this paper, we first describe our grain-size exercise and then discuss its advantages. In addition, we describe how we publicize this exercise in order to recruit introductory geology students to help collect sand samples for future grain-size analyses. Generating such interest results in a wide variety of sands for use in a grain-size analysis exercise, allows faculty without access to sediments in a nearby environment to do such a lab, and encourages introductory students to think about geology during visits home or while on vacation, especially during school breaks.

CONTEXT

Grand Valley State University (GVSU) is a comprehensive university with over 24,500 students (about 40% first generation college) located in western Michigan, which has a wealth of beach, dune, stream and glacial deposits. GVSU has a robust, active geology department, dedicated exclusively to undergraduate programs in geology and earth science (offering both majors and minors in these disciplines), with 11 tenure track faculty members, one affiliate faculty, a lab supervisor, and typically two visiting professors. The senior author has seven years of petroleum industry experience working in carbonate rocks, and 24 years of university teaching experience. The second author has 35 years of university teaching experience, and has coauthored numerous books on shoreline processes (e.g., Pilkey et al., 2011) and papers on projects that utilized grain-size analysis techniques (e.g., Middleton and Neal, 1989; Dias and Neal, 1990; Martinez et al., 2000; Barnhart et al., 2002).

Sed-Strat is taught winter semester with three hours of lecture and three hours of laboratory each week for 14 weeks followed by a final exam. Students in the course are almost all geology majors with an occasional anthropology major or geology minor. The majority of students take the course their junior year, so most have had courses in physical and historical geology, mineralogy, and igneous and metamorphic petrology. Because a two-course sequence in statistics is only one option with which geology majors can fulfill their mathematics requirements beyond college algebra and trigonometry, few have had statistics. Although in recent years Sed-Strat has had an enrollment of 16–22 students, one semester we did the same grain-size exercise with an enrollment of only four students. And, although the geology department is quite large for a totally undergraduate department, the same basic exercise was done when the department consisted of only four, tenure-track faculty members. Approximately 50% of our geology graduates go on to graduate school, and most of the rest go into industry (in the last five years, 27% into resources and 23% into environmental firms). (See JGE Supplemental Material for list of graduate schools and employers for 2007–2011 graduates. Available online at: http://dx.doi.org/10.5408/11-279s1).

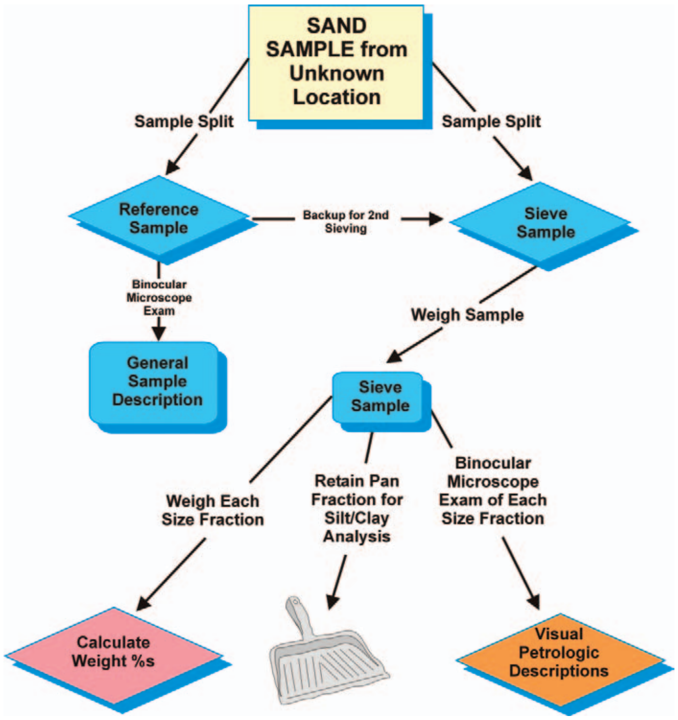

FIGURE 1: Diagram outlining laboratory exercise. Samples are processed using a RX-29 Ro-tap, and U.S.A. Standard Testing Sieve No. 10 through 230 (¼ phi interval). The lower left field is continued in Fig. 3, and the lower right field is continued in Fig. 4.

EQUIPMENT NEEDED

A mechanical shaker (e.g., Ro-tap), scale (to 0.01 grams), sample splitter, 8-inch-diameter sieves, and binocular microscopes are the main equipment needed. We use a RX-29 Ro-tap and sieves (USSS Nos. 10–230 cover the sand size range) at a ¼ phi interval as suggested by Folk (1974, p. 33), but ½ phi or even 1 phi intervals would be acceptable if the main purpose of the lab is to teach the students the technique and accuracy is not of great concern. Also, sieves could be initially purchased at a ½ or 1 phi interval and then more added when additional funds become available. A small sample splitter is also desirable in order to divide the sand samples (collected in a small Ziploc® bag or a jar) in an unbiased manner and also so that students learn the proper technique to split samples. We use small, plastic, petri dishes, 50 mm in diameter and 9 mm in height (Fig. 2) with tops for weighing and storing the size fractions. Plus, binocular examination of the samples is done with the sand in the same dishes. Each group of students is provided with a preassembled set of dishes with the unknown sample designation (e.g., A, B, C, etc.) and sieve size (e.g., USSS No. 10, 12, 14, etc.) permanently marked on each dish. We do not reuse the sand samples so they are discarded, but the sets of dishes are cleaned and retained for reuse. The appropriate set of dishes in a large Ziploc bag is given to each group, and the students do not receive a grade for the lab until the dishes are cleaned and returned!

PROJECT IMPLEMENTATION

Sample Collection

Although GVSU is located in an area rich in sediments, such a setting is not necessary to do the exercise outlined herein. We have built a sizeable collection of supporting sand samples that can be assigned in Sed-Strat as "unknowns" that are also used in other courses to illustrate a variety of geologic concepts. In addition to using the sand collection in physical geology labs, we can use the collection when lecturing about sediments, depositional environments, or provenance in introductory courses and, at the same time, encourage more sample contributions. Others have recognized the instructional usefulness of such collections (Kennair and Railsback, 2004), including the development of K–12 lesson plans around such sets (Giesen and Anderson, 2010). An ample, well-illustrated, non-technical literature on sands and sand environments (Greenberg, 2008; Welland, 2009; Pilkey et al., 2011) can be put to good use in the K–12 environment.

In our case, collecting sands and continuing to expand the sand reference set has created a link to faculty and to students in other courses as they are encouraged to collect samples for the department collection, usually during their travels. When a student in an introductory course such as environmental or physical geology asks for an excused absence for an early departure for a trip during a school break, a typical bargaining chip is, "Yes, you can leave early as long as you bring back a bag of beach/dune/stream sand with the sample location indicated, along with some information about the area where you collected the sample," along with a brief explanation that the sample may be used as an unknown for students in an upper level course. These samples, collected in a simple Ziploc bag or a jar, do tend to be biased toward resort beaches and dunes, but we aren't likely to be visiting Acapulco, Rio, Costa Brava, or even Daytona Beach in our geologic travels, so sample collection at such locations is a service to the department. Alternatively, students are happy to collect a sample for very few "extra credit" points (typically worth 1% of their grade).

We are constantly fine-tuning the requirements for introductory geology students to receive credit for delivery of a sand sample, but have found it works best to describe the opportunity to collect a sample both in class and via e-mail (and/or on Blackboard or a similar system, if available). We then require that the student send an e-mail, preferably while they are still "on location," stating the geographic location in which the sample was collected, the depositional environment (beach, dune, or stream), the energy level during deposition of the sand, the dominant mineralogy of the sample, and any observed anthropogenic changes to the depositional environment, such as those caused by engineered structures on a beach, dune, or stream, or beach nourishment bringing in a non-native sand (See JGE Supplemental Material for example of an e-mail sent to students. Available online at: http://dx.doi.org/10.5408/11-279s1). By requiring such information in an e-mail, a conversation results in which student misconceptions can be identified and corrected. For example, almost all the students report the depositional setting represents "low energy" even though they have "learned" that sand indicates a relatively high energy environment. An example of one such e-mail conversation began with a student reporting that he "went into the woods . . . and found a dry creek bed

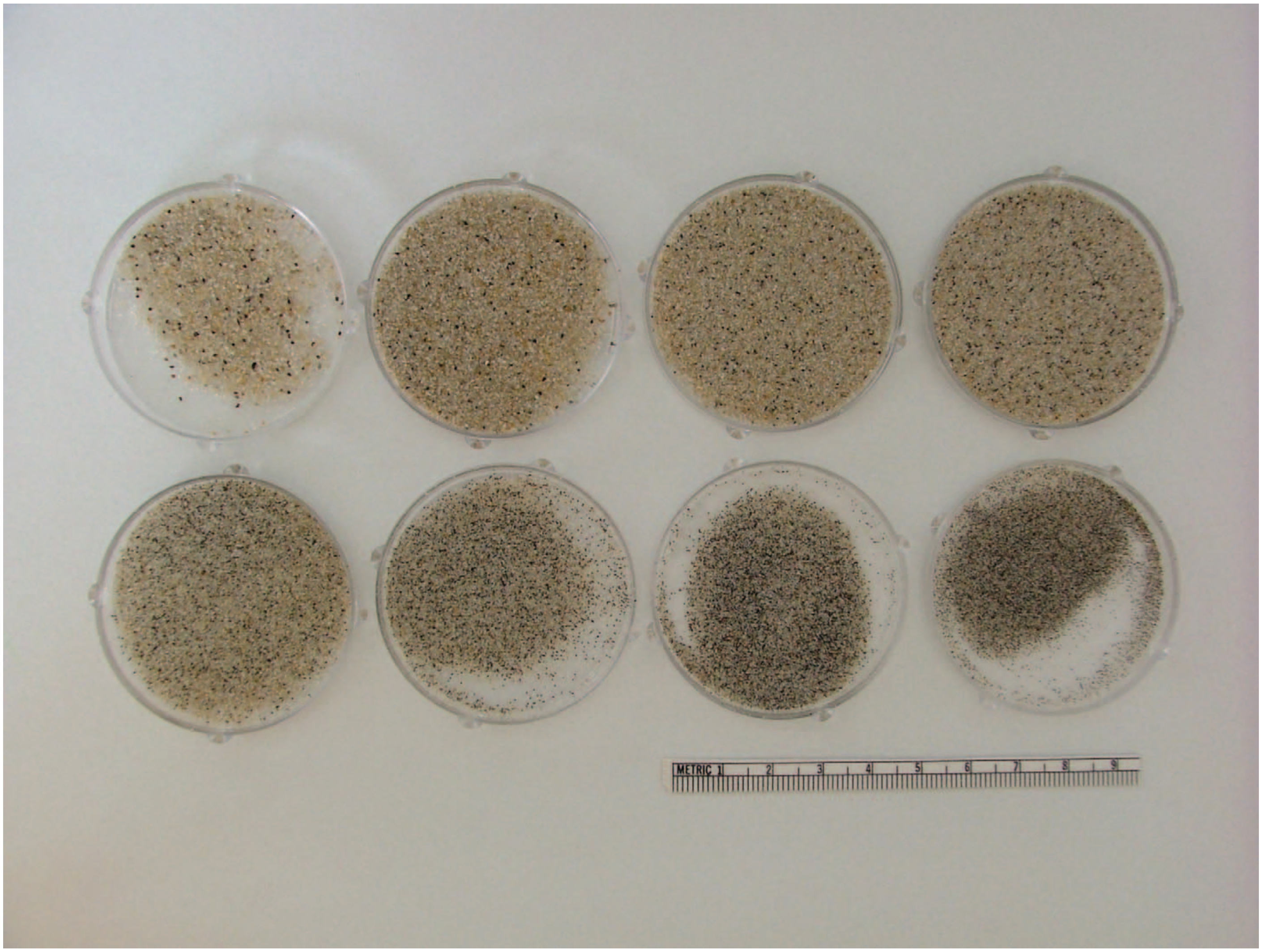

FIGURE 2: Separate size fractions of a dune sand from Sea Bright, New Jersey. As the grain size decreases, the amount of heavy minerals increases. Grain size decreases from upper left to lower right.

and followed it to the stream it flows into." He found that "the sand was very white and fine . . . like beach sand that you would find at Lake Michigan which is only a few miles away." The student went on to say that the sand indicates "low energy levels" and from what he "saw the stream was natural, it meandered and there were no dams or concrete." After a reply e-mail questioning the energy level reported by the student, the e-mail conversation ended with the student stating, "I would agree with you and say that the water moves fast because on the logs . . . that were in the dry bed lots of leaves were wrapped around the wood like they got caught on them and the water current made the leaves form to the logs." In this case the student was not in an exotic locale, but in his "own backyard" where he explored a streambed and thought about geology during his spring break, very likely something he would not have done without a little coaxing. Another advantage to requiring an e-mail conversation is that it forces communication between faculty and student. Especially in a large class, this may be one of the few times that we have a one-on-one conversation about geology, even if it is via e-mail!

The pleasant surprise has been that, like the student above, the nonscience students not only deliver the samples, but they are enthused about where they collected them and the observations they made on site. And, like this student, commonly their attention is drawn to geology in the field for the first time without the benefit of a professor standing by their side. Occasionally, the same student may show up later with another sample from a faraway place that they have visited.

But not only introductory students are involved in sample collection. Former Sed-Strat students who have gone through the exercise also like to challenge those who follow by bringing back sand samples from field trips, field camps, and postgraduate employment or travel, just as they occasionally deliver a rock or fossil that they think we would particularly appreciate. Past Sed-Strat students and alumni seem to especially enjoy collecting sand samples that may be a particular challenge for the Sed-Strat students. Faculty colleagues take part as well: we have had contributions from our volcanologist, metamorphic petrologist, paleoclimatologist, and lab supervisor. Such "gifts" from our colleagues, alums, and current students help build

TABLE II: Outline of the four-week long project on sieving.

Week 1
• Students introduced to sieve analysis technique in 3 hours of lecture and one 3-hour-long lab. Topics include:
Histograms and cumulative frequency (arithmetic and log-probability ordinates) graphs
Determination of statistical parameters (mean, median, mode, sorting, skewness, kurtosis), and their possible interpretations
• Unknown sand sample given to each group of typically 3 students
Weeks 2 through 4
• Additional lectures given on grain shape (sphericity, roundness, surface texture), grain transport, provenance, depositional environments, and other related topics
• Outside of class/lab time, students:
• Sieve using Ro-tap
• ¼ phi sieve intervals
• Complete analysis requires 2 to 4 nests of 6 sieves each
• Each nest is run for 15 minutes
• Construct graphs
• Calculate statistical parameters using Folk and Ward's (1957) equations (alternatively, students may be allowed to use computer software for calculations)
• Make visual estimates of grain shape and mineralogy for individual size fractions using a binocular microscope; construct a table summarizing the data
• Interpret origin of sample and write report discussing results
Additional notes
• All students in each group are required to take part in all aspects of the project
• Report counts for 3% of course grade
• A second lab project is initiated in the 2nd week introducing grain-size analysis of clay/silt samples using a Spectrex PC-2000 laser particle counter, which automatically graphs data and calculates statistics (exercise counts for 1% of course grade)

community and an appreciation for each other's subdisciplines. Over the years, the analysis of unknown sands from around the world in Sed-Strat has become a tradition in our department, one that most of our geology majors are aware of long before they take the course.

Student Preparation and the Exercise

As detailed in Table II, after the students read about grain-size analysis in their textbook, an introduction to grain-size analysis and use of the equipment is given in lecture (3 hours) and lab (3 hours). Beyond that, the students do the actual sieving and related work outside of lab time, typically over a four-week period early in the semester (Table II). Students are broken into random groups, typically of three students, and each group "draws" for an unknown sample. As shown in Fig. 1, the students first divide the sample using a sample splitter and the remainder is kept in reserve for microscopic examination and possibly a second sieving if the students want to check the precision of their results or if they have a mishap with their sample. (See JGE Supplemental Material for the actual lab assignment. Available online at: http://dx.doi.org/10.5408/11-279s1) Binocular microscope examination allows the students to qualitatively characterize their bulk sample (e.g., mean grain size, sorting, and mineralogy) for later comparison to their quantitative results. Not only do the students compare their initial observations of the bulk sample to their more quantitative observations following sieving, but also the careful examination of the initial sample may lead to recognition of contaminant grains picked up from the sieves when the individual size fractions are examined. Such contamination from students not properly cleaning sieves after use is one of the drawbacks of this method.

Once sieving is complete, the size fractions (Fig. 2) are weighed, a histogram and two cumulative curves are made (arithmetic and log-probability ordinates), and statistical parameters (mode, mean, median, sorting, skewness, and kurtosis) are determined (Fig. 3). We prefer that the students calculate mean, sorting, skewness, and kurtosis by hand using Folk and Ward's (1957) formulas and phi values from the students' log-probability graphs so that the students know how the statistical parameters are determined. In order to help the students keep all the needed numbers straight and calculate the values needed to construct their three graphs, we supply them with a blank form modeled after the "DATA FORM" in Folk (1974, p. 34). We go over Folk's method in great detail in class using his filled in form and showing the students how to fill in their blank forms in the same way, step-by-step, using their own data. (See JGE Supplemental Material for a copy of the data form we use and examples of some students' work. Available online at: http://dx.doi.org/10.5408/11-279s1)

Figure 4 shows the visual observations that are made of the size fractions from sieving (Fig. 2) that cannot be done with LD or settling tube methods. The students examine the size fractions and give percentage estimates of mineral composition aided by visual percentage charts (e.g., Compton, 1985; Coe et al., 2010) (modified Compton charts are available on line at www.usouthal.edu/geography/allison/gy303/MineralPercentageEstimateCharts.pdf; accessed 21

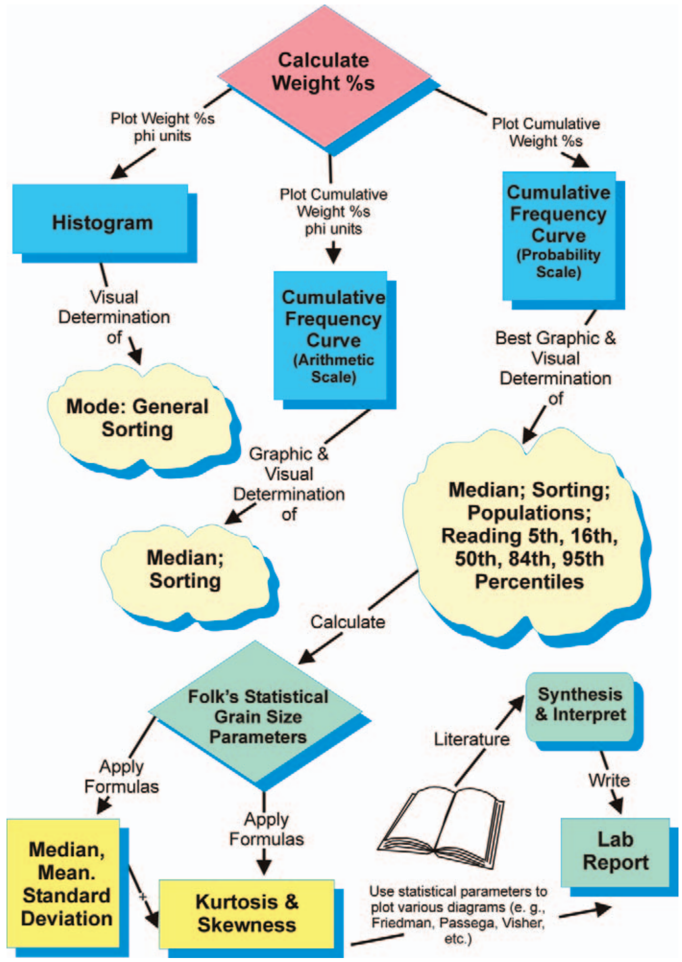

FIGURE 3: Diagram outlining steps for making plots of grain size data and calculating statistics.

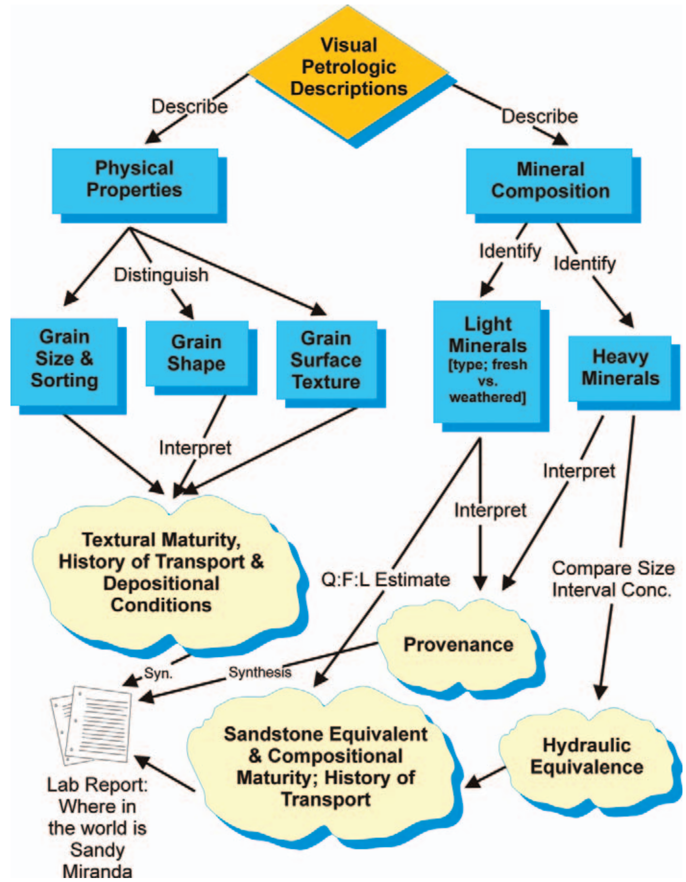

FIGURE 4: Diagram outlining steps for the visual examination of samples and possible interpretations students might make.

May 2012), estimates of grain properties such as sphericity and roundness using Powers' (1953) chart, and descriptions of the surface textures of the grains (primarily polished versus frosted). In many cases, not all of these data can be estimated for the finest size fractions, and the students make note of that in the table they construct for their report. For all of the microscopic data collection, we encourage that each student in the group make an estimate for all the data and for each size fraction. Then the students can make sure that they are coming up with similar estimates and take an average for each observation. (See JGE Supplemental Material for an example of tables showing some students' data. Available online at: http://dx.doi.org/10.5408/11-279s1)

Data Analysis

Following collection of all their data (grain size, grain shape, and mineralogy), construction of graphs, and calculation of statistical parameters, the students use their data to make their interpretations and write their reports (Fig. 4). As shown in Table II, by then the students will have done more reading in their textbook (Boggs, 2012) and journal articles, heard lectures, and done in-class activities on topics such as grain shape, grain transport, provenance, and depositional environments. (For a good review of basic concepts of grain-size analyses and their interpretation including data plots and the use of statistical parameters see Davies-Vollum, 2006.) We emphasize the difference between results and interpretations and require that, in their reports, the students keep their results and interpretations clearly separate. We stress that even though their interpretations may not be correct, their results will still be valid. Although the students' main goal for the interpretation section of their report is to try to determine if their sample was deposited on a beach, dune, or stream, we also request that they speculate about the provenance of their sample and direct them to the Dickinson et al. (1983) ternary plots to consider possible tectonic settings.

Shortcomings in Student Interpretations

Students usually do a good job on the mechanics of sieving and making graphs. The quality of their visual examination of their size fractions varies widely from group to group, but most do at least a satisfactory job. However, when it comes to interpreting their data, they have considerably more problems. Despite being warned that grain-size analysis is not the "black box" sedimentologists had originally hoped it would be for fingerprinting a sand's depositional environment, students still tend to think that plotting their results on a diagram such as a skewness versus standard deviation plot from the literature (e.g., Friedman, 1967) will certainly tell them the correct origin of their unknown. But typically about half the students are incorrect in their interpretation of the depositional environment. The number of incorrect interpretations helps us again explain that many of the same processes operate in different depositional environments making interpretation of the environment using grain size problematic. Although this information is stated in their textbook (Boggs, 2012, p. 56), it becomes much more real for the students when they learn the success ratio amongst their peers. Moreover, the exercise gives us a perfect opportunity to once more drive home the message that the results of their analyses are still valid even though their interpretation may be incorrect. We consider the fact that half the class does not get the "right" answer to be one of the most important aspects of the exercise; science is a process and a scientist can only make the best interpretation possible with the data available. We also stress the need to use all data available when making an interpretation. Some students have the tendency to use only the grain size data and to ignore the grain shape and mineralogy data that they so painstakingly collected. By requesting that the students give special consideration to sediment source, they will at least reflect on the mineralogy of their samples, so in the future, we plan to put more emphasis on provenance.

Trying to entice students to pay attention to the detail in their plots is also difficult. For example, few students initially suggest that the line segments on their log-probability cumulative curve might represent different subpopulations, perhaps transport by traction, saltation, and suspension as suggested by Visher (1969), and commonly make no mention of the line segments at all even though almost all the students show the line segments on their curves. Although such an interpretation of these plots is controversial, as reviewed by Davies-Vollum (2006), the students should still discus the line segments, citing the controversies. We believe most students do not discuss the plots in terms of Visher (1969) because they know they are controversial, which leads them to believe they do not need to discuss them at all, despite our attempts to make them think otherwise. In the future, specific discussion of these line segments will be added to the lab and grading rubric, which, based on previous additions of detail to the grading rubric as discussed below, will very likely help students understand the controversies.

Likewise, other possible interpretations are commonly missed by students. For example, some groups do not discuss the possibility of mixed sources, reworking, or winnowing effects when their sample is bimodal or strongly skewed. We have found that during the few weeks the students are working on this project, at the start of lectures or labs it helps to show a grain size plot or statistical parameters and hold a short discussion on possible interpretations. But, in the end, students still need to be encouraged to go back and rethink their interpretations, to read the literature, to discuss the data with other students in their group, to compare their graphs to those of other groups, and to incorporate all their data into their interpretations, including their visual observations.

Grading

Students are informed at the start of the project that in no way is their grade dependent on figuring out the correct depositional environment, but, rather, their grade is in part dependent on how they support their interpretations. In fact, they are told before they start the project that typically only half the groups correctly determine the environment of deposition. We find that it helps to drive home the point that deciphering depositional environments using grain-size analysis and textural/mineralogical observations is challenging by telling the class, literally minutes after they hand in the lab, the interpretation of the environment each group made followed by the correct environment. With a little bit of theatrics and by building up the suspense for each group, the event is also great fun! After declaring something like, "Group A said their sample is from a beach and . . . (pause) . . . it is actually from . . . (longer pause) . . . a dune," roars of approval or disappointment typically go up from the class. And there is the added fun of telling the students their sample location ("Where in the world is Sandy Miranda," Fig. 4). That can also be played up by, for example, a string of exotic settings like a beach in the Greek Isles, a stream in Bolivia, and a dune in Madagascar can be followed by . . . (pause) . . . a Lake Michigan dune only 20 miles away! This, too, typically provokes groans from the students. After the fun is over we discuss why determining the depositional environment is so difficult and why going through the exercise is still important.

In the past three years grading has been done with a rubric, which, like the exercise as a whole, is constantly being improved. For purposes of this paper, we have included a general grading rubric along with some of our department goals juxtaposed against components of the exercise described herein (Appendix A), but when actually grading the lab, a more detailed but simply designed rubric is used. (See JGE Supplemental Material for the grading rubric. Available online at: http://dx.doi.org/10.5408/11-279s1) We have found that providing the students with a very straightforward, but detailed, grading rubric (mostly just a check list with points added) well before their lab is due, results in greatly improved reports even though the rubric merely repeats the points they need to cover as outlined in the lab exercise. Their attention to detail is especially improved when provided with the rubric, probably in part because the students realize all the details do indeed count toward their grade.

Because the students work in groups, special attention is required to assure that all the students in the group are doing their fair share of the work in all aspects of the lab. As a result, the students are required to initial the activities in which they took part on the lab assignment and turn it in with their report. (See JGE Supplemental Material for the "Sieve Analysis Laboratory." Available online at: http://dx.doi.org/10.5408/11-279s1) To reduce the amount of work (and grading!) required for this lengthy, time-intensive lab, the students are allowed to hand in one report per group, in which they share writing tasks, and one set of data tables. As a check on accuracy, they are instructed to each calculate the statistical parameters and then compare their numbers. Because we believe making their own graphs is an essential component of understanding grain-size analysis, each student is required to produce their own set of three graphs. Occasionally a student does not take part in all aspects of the lab or does not make his or her own graphs. In that case, the student's points are docked by 20%. (See Appendix A; and JGE Supplemental Material for grading rubric. Available online at: http://dx.doi.org/10.5408/11-279s1)

TABLE IIIA: Summary of student evaluations of the lab exercise (n = 20).[1,2]

Question: Did the exercise help you better understand . . .	Average Response
1. the mechanics of doing grain size analysis?	4.5
2. the range of sand grain sizes and degree of sorting?	4.2
3. the phi system?	4.0
4. the graphs used to plot grain-size distributions, and their use to extract data for quantifying the descriptive measures?	4.1
5. the calculation of statistical parameters for grain size analysis?[3]	3.8
6. what the statistical parameters tell about grain size distribution (e.g., the significance of mean, skewness, sorting)?[3]	3.6
7. why microscopic examination of the whole sample, as well as individual size fractions, adds to understanding size distribution, and interpretation of textural and compositional significance?	4.0
8. strengths and weaknesses of "fingerprinting" sand's environment of transportation and deposition based on the grain-size statistics?	4.1

[1]Scale of 1–5, where 1 = no, not at all; to 5 = yes, very much so.
[2]For quotations from students corresponding to numbers 1–8, see Table IIIB.
[3]The lower scores for numbers 5 and 6 resulted where the student respondents indicated they already knew these calculations and their application from having had statistics courses.

PROJECT ASSESSMENT

Student Assessment

Because we have been doing a sieving exercise using unknown samples for a number of years, we have no baseline assessment data for the other ways we ran the grain-size analysis lab. However, an assessment survey involving 20 students indicates the current exercise does a good job in achieving our objectives, learning the mechanics of doing a grain-size analysis using sieving, plotting the data, calculating statistical parameters, understanding why binocular observations of size fractions adds to the analysis, and understanding the limitations of grain-size analysis in regards to determining an environment of deposition (Table IIIA). Perhaps more important than the results of the numerical scores given in Table IIIA are some of the comments made by students, a sampling of which are given in the Table IIIB.

Advantages of Using Sieving

We prefer sieving for a variety of reasons over the other alternatives. First, sieving is not a "blackbox" technique; even precollege students can easily understand the process and principles involved. In fact, providing the sediment is dry, sieves can be used in the field to give all levels of students (K–16) a sense of the grain-size distribution of the sediment as they study a particular depositional environment. Second, sieving is a widely used method and has a long history of presentation in textbooks (Folk, 1974; Boggs, 2012) and the research literature. Third, sieving is the least expensive in terms of necessary equipment and maintenance (Table I). And, fourth, following sieving, size fractions of the sample are available for visual observations using a binocular microscope.

In order to construct accurate plots and obtain accurate statistical parameters from their raw data, after sieving the unknown, students must carefully weigh the individual sieve size fractions (Figs. 1 and 2) and are, thus, fully involved in data collection. They then plot the size-distribution data by hand and calculate statistical parameters (Fig. 3). As shown by numbers 4 and 5 in Tables IIIA and IIIB, by generating the plots "by hand" the students understand the origin of the numbers that they then use to calculate the statistical parameters, also done "by hand" using formulas. The students do not have the option of hitting a button on a piece of equipment and mysteriously receiving statistical parameters and plots! As a result, students are much more likely to understand exactly what the data are showing (numbers 4 and 5 in Tables IIIA and IIIB) and to catch possible errors during data collection. However, students also are encouraged to follow up their results by utilizing software programs to input their data and calculate statistics and make plots using a computer if they are so inclined (e.g., GRADISTAT, Blott and Pye, 2001).

We also prefer the use of sieves because size-fraction subsamples are preserved for visual observations using a binocular microscope (Figs. 2 and 4). The size-fraction subsamples allow the students to generate data on variations in grain composition, shape, and weathering with change in grain size. For example, the typical concentration of heavy minerals in the finer sand fractions becomes more apparent following sieving (Fig. 2). These visual observations strongly support the statistical parameters in interpretation of grain source(s), modes of transport, depositional processes, and depositional environments. Size-fraction textural and compositional differences help make interpretations involving mixed populations, multiple sources, and selective sorting. Finally, evaluation of grain compositions is important in suggesting an economic use for the sediment. Table IV presents selected quotes from student reports that demonstrate the observational skills and thought processes that develop due to the students' visual observations made on grain size fractions.

Observations of the size fractions also aid the students when they begin classifying and interpreting the origin of sedimentary rocks. Most of the Sed-Strat students are making a transition from their experience in working with hand specimens and thin sections of igneous and metamorphic rocks in a petrology course to mineral identification in loose sediment prior to studying sedimentary rocks. Recognition of the variety of heavy minerals and sand-sized

TABLE IIIB: Selected student quotes corresponding to question numbers 1–8 in Table IIIA.

1. *Yes, sieving is easier said than done, so getting that hands-on experience is necessary.*
Yes, we got to use the equipment and actually work it out.
Yes, it is helpful to understand the variety of grain sizes in a deposit. This was the first true analysis that I have done. Very useful.
2. *Looking at our samples under a microscope we could see our grains were not all the same size . . . the sample appeared to have a small range of sizes, but upon sieving, we had 12 sizes!*
Yes, working hands on with the sand helped us see the range of sizes.
Yes, it forced us to actually look at grains and study them individually.
Yes, I didn't realize how much variety of grain sizes are actually in sand.
3. *Yes, the lab forced us to really understand the math behind it.*
Yes, after calculating statistics the unit of phi made sense.
Yes, I had no idea what this was, and to actually use *it was beneficial.*
4. *Yes—it's one thing just to read them, another to figure out how to actually make them.*
These graphs and their interpretations were quite helpful, as I have always focused on non–stats-based math so this gave me some practice.
Yes, because we had to work through them.
It helped emphasize the importance statistics plays in geology, especially since many of us only take the calculus courses. Actually making and then using the graphs was helpful.
Calculating all the statistics made me look at the graphs.
This was the first experience of actually doing the work and understanding it. They have only been referenced as a figure to look at in the past.
5. *Yes, it helped to actually use the formulas to see specifically how they work.*
The calculation helps you to more clearly see where the numbers are coming from instead of just being given to us.
6. *Yes, went back over notes and discovered useful things about the parameters.*
Yes, it definitely helped me better understand skewness and sorting.
Before they would have just been a figure I flipped through and just "thought" I understood.
7. *Yes, it was interesting to see how the grains became more spherical as diameter decreased.*
I had to spend a fair amount of time with the binocs and it strengthened my estimation skills.
Yes, looking at the grains firsthand and having to describe them was very helpful in understanding what it means.
Yes, roundness and sphericity could be seen very *well through it and was very useful that way.*
Yes, looking at the grains up close and personal really put things in perspective—helped a lot.
8. *Yes, can't only use sieves, need to look at the sample/mineralogy as well.*
Yes, it still is difficult to determine the environment—much harder than I previously thought!
Well, we were wrong so I guess it shows us how there can still be uncertainty.
Yes, this was the most important part I think. It's one thing to do the sieving and analysis but another entirely to conclude what it means.
Small details can be the determining factors of a depositional environment such as frosted vs. polished grains. A missed detail may result in inaccurate interpretation.
Yes, some environments were easy to rule out, but others that have similar characteristics were hard to decipher. Using all the data available and creating an interpretation was useful.
Yes, we only got 50% accuracy class-wide. It showed me how a real-world analysis would be.
Strengths—determining stats to tell grain size and sorting. Weakness—accurately interpreting stats into environment.

rock fragments in sedimentary rocks is easier after studying loose sand samples, as is recognition of grain size divisions (e.g., coarse sand, medium sand, or fine sand). Encouraging the students to use visual observations is important not only because it builds on what they learned in petrology, but also in historical geology and mineralogy. Their observations reinforce what they have learned about mineral properties and settling dynamics (e.g., hydraulic equivalencies with heavies concentrated in finer grain-size fractions; Fig. 2), grain shape variations with size (e.g., coarser grains generally being more rounded; selective sorting of carbonate grain types), and weathering (e.g., concentration of rock fragments in coarser size fractions).

Advantages of Using Unknown Sand Samples

In designing sieving exercises at GVSU we have tried using random, known sand samples; sample sets from local streams, Lake Michigan dunes, beaches, and near-shore sand bars; sample sets from beach transects (similar to Davies-Vollum, 2006); and the use of "unknowns" derived from various worldwide environments as described herein. In all but the latter case, students were aware of the general

Table IV: Selected quotes from student's reports demonstrating typical observations and interpretations made by examination of grain size fractions using a binocular microscope.

The significant quantity of angular olivine present suggests proximal basaltic highlands, as might be found on an oceanic shield volcano setting.
The overall lack of frosting on the grains helped to negate . . . a dune environment.
The grains became more rounded as they got coarser.
The grains were angular, which is not a very common characteristic of a beach . . . We also found that there is a significant amount of feldspar, mostly in our largest sieve sizes. Feldspar usually weathers very quickly on a beach where it is being pounded by waves. So after taking these possibilities into account we decided sample C is a river sand.
The mineral content of the sample is comprised largely of polished quartz, feldspar, magnetite, and trace amounts of olivine.
Because the quartz grains are mostly sub-rounded to rounded, a beach or dune environment may be possible. However, stronger evidence for a beach deposit exists in the fact that the quartz grains are polished rather than frosted.
The high amount of lithics and feldspars indicate a lower energy environment than a beach or dune.
The dominant mineralogy of our sample is quartz, which ranged from about 50%–90% in the varying phi intervals. The quartz grains ranged from sub-angular to sub-rounded, and varied between polished and frosted. In our finer samples, we saw an abundance of magnetite, as compared to the coarser samples, which were dominantly quartz with minor mafics (such as garnet and an unknown green mineral).
Some of the more angular grains might not have traveled that far, as they would have been smoothed through transportation.

source of their sample(s) for analysis, resulting in some bias in their interpretations and limiting the breadth of natural variation seen in sands across the total class sample set. We concluded early in our experience that using unknown sand samples from a beach, dune, or stream provided a challenging exercise for the students, stimulated the students' curiosity (most people love a mystery!) and observational skills, generated independent interchange of ideas between students when comparing their results, best demonstrated the difficulties of identifying the correct depositional environment using grain-size analysis, and was the most practical in terms of providing samples. GVSU's Sed-Strat course is taught winter semester, and the sieving exercise is typically done early in the semester, so our local wealth of sandy environments are usually snow covered, which eliminates a field exercise to collect the samples for grain-size analysis. Finally, by using unknowns, introductory geology students, geology majors who have completed Sed-Strat, alums, and faculty colleagues are all involved in providing samples.

USING SIEVING BEYOND THE LAB EXERCISE

In addition to the standard Sed-Strat lab exercises, our students are required to do a small-scale research project and present their results at GVSU's Student Scholars Day held annually in April. As western Michigan is lacking in rock outcrops, typically many students opt to do sand studies based on sieving. Indeed, some of these projects are similar to that described in Davies-Vollum (2006) in that students attempt to differentiate known subenvironments at a beach, dune, or stream using grain-size analysis, but they have the added benefit of also being able to perform visual observations of the size fractions. Some students opt to study silt- and clay-sized sediments using our laser particle counter (LPC; Spectrex PC-2000), which automatically does "all the work" for them, but at least by then the students have an understanding of grain-size analysis from the sieving exercise. In fact, during the time the students are working on their sieve exercise they also do a small-scale project analyzing fine (coarse clay to very fine sand) sediment using the LPC (Table II), so they become familiar with the instrument while taking Sed-Strat.

The lessons learned in doing this exercise are also applied in the courses students typically take after they have completed Sed-Strat such as Geomorphology, which is a required course. Students also will use the information learned if they take Glacial and Quaternary Geology, Geohydrology, or Engineering Geology as one or both of our two required electives. In fact, in Engineering Geology the students do a basic sieve analysis for a site assessment project.

In addition, the sieving project has opened doors for many students. A number of students have used grain-size analyses in research projects with our glaciologist. For these projects involving glacial sediments with a wide range of grain sizes, they commonly use both sieving and the LPC, and sometimes use a statistics program, GRADISTAT (Blott and Pye, 2001) which automatically calculates grain size parameters using either Folk and Ward's (1957) graphical method or the Krumbein and Pettijohn's (1938) mathematical "method of moments," but by then the students have had the experience of doing their own calculations. In addition, sieving is a procedure used by many environmental and engineering firms that deal with materials and reservoir characteristics. Consequently, several students have obtained jobs or internships at least in part because they were familiar with sieving techniques and many small environmental consulting firms do not have equipment other than sieves for grain-size analysis. (In fact, one of our local alumni who owns a small environmental firm asked if he could purchase an old Ro-tap from us!) Indeed, over the years we have received several calls from employers specifically asking if we have students who have used sieving for grain-size analysis. Although the employers are mostly interested in grain size for material science or porosity and permeability studies rather than sediment origin, the technique is the same and the students require little training.

CONCLUSIONS

Our favored approach for grain-size analysis for undergraduate, sedimentology students is sieving because this method is very "hands on" emphasizing the plotting of raw data in various graphs, manually calculating statistical parameters, and allowing for visual inspection of the size fractions for mineralogical and shape information. The latter may be critical information for helping students hypothesize about transportational/depositional conditions and provenance. Using unknown samples along with sieving serves to focus the students' attention on solving an interesting question using all data available. Additionally, using an unknown sand allows for a certain numbers of "failures" in which the students do not predict the depositional environment correctly. That, in turn, results in discussions about the durability of results and that even good, reasonable interpretations may be wrong. Using unknown samples also allows for faculty located at schools with a dearth of sediments available for study to still carry out lab exercises involving grain-size analysis. Furthermore, by arranging for introductory geology students to collect sand samples for sedimentology students to study, the introductory students are not only providing a service, but they are also thinking about geology when they might otherwise merely be "catching a few rays" on spring break!

Acknowledgments

We thank a multitude of Sed-Strat students for spending many hours in the lab sieving unknown sand samples; introductory geology students, geology majors, alumni, and faculty colleagues for providing unknown sand samples; Larry Fegel and Figen Mekik for technical assistance; and two anonymous reviewers for JGE whose suggestions greatly improved the manuscript.

REFERENCES

Barnhardt, W.A., Gonzalez, R., Kelley, J.T., Neal, W., Pilkey, O.H., Jr., Monteiro, J.H., and Dias, J.A. 2002. Geologic evidence for the incorporation of flood tidal deltas at Tavira Island, southern Portugal. *Journal of Coastal Research*, SI 36:28–36.

Blott, S.J., and Pye, K. 2001. GRADISTAT: A grain size distribution and statistics package for the analysis of unconsolidated sediments. *Earth Surface Processes and Landforms*, 26:1237–1248.

Boggs, S., Jr. 2012. Principles of sedimentology and stratigraphy, 5th ed. Upper Saddle River, NJ: Prentice Hall. p. 585.

Coe, A.L., Argles, T.W., Rothery, D.A., and Spicer, R.A. 2010. Geological field techniques. New York: Wiley-Blackwell. p. 323.

Compton, R.R. 1985. Geology in the field. New York: John Wiley & Sons. p. 398.

Davies-Vollum, K.S. 2006. Using grain size analysis as the basis for a research project in an undergraduate sedimentology course. *Journal of Geoscience Education*, 54:10–17.

Dias, J.M.A., and Neal, W.J. 1990. Modal size classification of sands: An example from the northern Portugal continental shelf. *Journal of Sedimentary Petrology*, 60:426–437.

Dickinson, W.R., Beard, L.S., Brakenridge, G.R., Erjavec, J.L., Ferguson, R.C., Inman, K.F., Knepp, R.A., Lindberg, F.A., and Ryberg, P.T. 1983. Provenance of North American Phanerozoic sandstones in relation to tectonic setting. *Geological Society of America Bulletin*, 94:222–235.

Folk, R.L. 1974. Petrology of sedimentary rocks. Austin, TX: Hemphill Publishing Co. p. 182.

Folk, R.L., and Ward, W.C. 1957. Brazos River bar: A study in the significance of grain size parameters. *Journal of Sedimentary Petrology*, 27:3–26.

Friedman, G.M. 1967. Dynamic processes and statistical parameters compared for size frequency distribution of beach and river sands. *Journal of Sedimentary Petrology*, 37:327–354.

Giesen, J.L., and Anderson, J.L.B. 2010. Sands of the world. *Geological Society of America Abstracts with Programs*, 42:2, 67.

Greenberg, G. 2008. A grain of sand: Nature's secret wonder. Minneapolis, MN: Voyageur Press. p. 112.

Hartmann, D., and Flemming, B. 2007. From particle size to sediment dynamics: An introduction. *Sedimentary Geology*, 202:333–336.

Hatfield, R.G., Cioppa, M.T., and Trenhaile, A.S. 2010. Sediment sorting and beach erosion along a coastal foreland: Magnetic measurements in Point Pelee National Park, Ontario, Canada. *Sedimentary Geology*, 231:63–73.

Hubbard, B., Glasser, N., Hambrey, M., and Etienne, J. 2004. A sedimentological and isotopic study of the origin of supraglacial debris bands: Kongsfjorden, Svalbard. *Journal of Geology*, 50:157–170.

Ingersoll, R.V., and Eastmond, D.J. 2007. Composition of modern sand from the Sierra Nevada, California, U.S.A.: Implications for actualistic petrofacies of continental-margin magmatic arcs. *Journal of Sedimentary Research*, 77:784–796.

Kennair, E.H., and Railsback, L.B. 2004. Beach and shoreline sands from around the world. Available at http://www.gly.uga.edu/railsback/sands/sandstitle.html (accessed 21 May 2012).

King, D.B., and Gavin, C.J. 2002. Coastal Sediment Properties. *In* U.S. Army Corps of Engineers, Engineering and Design Coastal Engineering Manual. Eng. Man. 1110-2-1100, Part III, Chap. 1. 1–41. Washington, DC: USACE.

Krumbein, W.C., and Pettijohn, F.J. 1938. Manual of sedimentary petrography. New York: Appleton-Century-Crofts. p. 549.

Manduca, C.A., Baer, E., Hancock, G., MacDonald, R.H., Patterson, S., Savina, M., and Wenner, J. 2008. Making undergraduate geoscience quantitative. *EOS, Transactions, American Geophysical Union*, 89:149–150.

Martinez, J.O., Gonzalez, J.L., Pilkey, O.H., and Neal, W.J. 2000. Barrier island evolution on the subsiding central Pacific coast, Colombia, S.A. *Journal of Coastal Research*, 16:663–674.

Middleton, G.V., and Neal, W.J. 1989. Experiments on the thickness of beds deposited by turbidity currents. *Journal of Sedimentary Petrology*, 59:297–307.

Passega, R. 1957. Texture as a characteristic of clastic deposition. *American Association Petroleum Geologists Bulletin*, 41:1952–1984.

Pilkey, O.H., Neal, W.J., Kelley, J.T., and Cooper, J.A.G. 2011. The world's beaches: A global guide to the science of the shoreline. Berkeley, CA: University of California Press. p. 302.

Powers, M.C. 1953. A new roundness scale for sedimentary particles. *Journal of Sedimentary Petrology*, 23:117–119.

Rodríguez, J.G., and Uriarte, A. 2009. Laser diffraction and dry-sieving grain size analyses undertaken on fine- and medium-grained sandy marine sediments: A note. *Journal of Coastal Research*, 25:257–264.

Sarocchi, D., Sulpizio, R., Macías, J.L., and Saucedo, R. 2011. The 17 July 1999 block-and-ash flow (BAF) at Colima Volcano: New insights on volcanic granular flows from textural analysis. *Journal of Volcanology and Geothermal Research*, 204:40–56.

Sawakuchi, A.O., Giannini, P.C.F., Martinho, C.T., and Tanaka, A.P.B. 2009. Grain size and heavy minerals of the Late Quaternary eolian sediments from the Imbituba-Jaguaruna coast, Southern Brazil: Depositional controls linked to relative sea-level changes. *Sedimentary Geology*, 222:226–240.

Visher, G.S. 1969. Grain size distributions and depositional processes. *Journal of Sedimentary Petrology*, 39:1074–1106.

Welland, M. 2009. Sand: The never ending story. Berkeley, CA: University of California Press. p. 343.

Wohletz, K.H., Sheridan, M.F., and Brown, W.K. 1989. Particle size distributions and the sequential fragmentation/transport theory applied to volcanic ash. *Journal of Geophysical Research*, 94:B11:15703–15721.

APPENDIX A: Selected, stated departmental goals for the geology major, exercise components, and general grading rubric for students' reports (outlined in the Sieve Analysis Laboratory[1]).

Goal	Exercise Component	Report Segment (supporting materials)	Points (%)
Use of analytical equipment	Sample processing, splitting, weighing, use of ¼ phi sieves and Ro-tap	Required to do lab	
Proficiency in data collection	Care in weighing and recording each size fraction	Table 1. Raw data table with title	3
	Calculation of weight % for each size fraction; post-sieving % weight loss or gain	Minimal % weight loss or gain	
Proficiency in graphical analysis skills	Construct 3 graphs, fully labeled axes, figure captions	Size Frequency Distribution:	25
		Figure 1. Histogram	
		Figure 2. Arithmetic cumulative curve	
		Figure 3. Probability cumulative curve	
	Using the graphs and formulas, calculate textural parameters	Table 2. Statistical parameters—summary with proper units	6
	Calculation Worksheet: mean, standard deviation, skewness, kurtosis	Note estimated mean and sorting vs. calculated values	5
		Include Calculation Worksheet	
	Verbal descriptions equivalent to the calculated parameters	Table 2. Verbal descriptions included with numerical values; "results only" paragraph with all statistics expressed verbally and numerically; table title	7
Understanding earth materials and processes; mastery of geologic concepts; solve geologic problems	Microscopic examination of the bulk sample	Estimated mean and sorting	
		General mineral composition	
	Microscopic examination of each size fraction	Table 3. Mineralogy, roundness, sphericity, surface texture with title; include in results only paragraph	15
	Interpretation: weathering, deposition, transportation processes; energy; depositional environments; provenance	Interpretation paragraph: support conclusions with reference to statistical parameters, graphs, microscopic descriptions, literature	12
Proficiency in scientific writing	Report is clearly written and in format called for in exercise; references	Results separated from Interpretation	7
		Proper English and spelling	
		Tables and figures cited in correct order	
		References properly cited	
Team Work	Group Project	Did fair share of work (signature sheet included)	20

[1]See JGE Supplemental Material for the lab assignment. Available online at: http://dx.doi.org/10.5408/11-279s1.