THE PROBLEM OF SAMPLE CONTAMINATION IN A FLUVIAL GEOCHEMISTRY RESEARCH EXPERIENCE FOR UNDERGRADUATES

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ABSTRACT

Geochemical analyses are difficult because all samples have an unknown composition. As most geoscience programs do not teach "techniques" courses, teaching analytical technique and critical data analysis becomes a priority during the undergraduate research experience. The analysis of rivers is an excellent way to teach geochemical techniques because of the relative ease of sample collection and speed of sample analysis. The sample collection and processing steps, however, are subject to a variety of mistakes that affect sample integrity.

This paper focuses on the potential sources of sample contamination during the sampling, filtering, and bottle cleaning processes, and reviews methods to reduce and detect contamination. Training at the beginning of a research program is helpful, but during a ten-week or shorter summer research experience, training time is of necessity short and much learning occurs in the actual research environment. An emphasis on contamination sources and the one million times dilution approach to cleaning will help avoid sample contamination. The cleaning process, though a critical analytical technique, is a tedious, dull, and seemingly menial task. As a result, faculty members engaged in undergraduate research experiences face a difficult task when teaching the need for cleanliness in the laboratory and field. The participating students, however, learn an important lesson of the need for "mindfulness" in the research process.

Keywords: Geochemistry; undergraduate; research; education

INTRODUCTION

Undergraduate research is becoming common at undergraduate colleges and universities. The goals of undergraduate research are multiple. Research projects give the professor insight into the abilities of the student, the student learns new techniques in the field and laboratory, and most importantly, the student learns problem-solving skills that are useful in a variety of settings. One of the major goals, however, of any undergraduate research experience should be the generation of high quality data. The need for high quality data goes beyond the immediate need of the professor; the generation of high quality data forces the student to develop a professional manner.

As the geosciences become ever more quantitative, and as quality laboratory instruments become common at undergraduate institutions, the push for high quality data increases. A major difficulty for faculty at undergraduate colleges and universities is that undergraduate research is a delicate balancing act. The students tend to be intellectually immature and often require far greater training and oversight than graduate students. This is especially true during the academic year, when undergraduate students must balance academics with involvement in a research program. Summer research experiences are more focused, but training and oversight are compressed into a time period of ten weeks or less. At the same time, the quality of the data collected is dependent on the skills of the undergraduate student. Conversely, the quality of quantitative data is dependent on analytical techniques that are simple and tedious, such as the art of properly cleaning laboratory equipment.

I use the cleaning analogy for two reasons. First, this analogy is similar to Thict Naht Hahn's use of washing dishes to practice mindfulness (Hahn, 1987). Simply stated, mindfulness is the idea of living in the moment, focusing fully on the task at hand, leaving thoughts of the future and past behind. Only then can washing the dishes move from an odious task to an enjoyable part of simply being alive. You also get cleaner dishes. Therein lies the second reason for using this analogy. In geochemical research of the natural environment, "clean dishes" are an essential starting point of laboratory analysis. The "clean dishes" analogy can be extended to nearly every step of sample processing including collection, filtering, and preparation of water samples for chemical analysis.

Unlike more lab-based and experimental science done in biology and chemistry, most geoscientists work primarily with samples that have unknown chemical compositions. Errors in analysis can quickly compound due to sample contamination at every step in which the sample is handled. This is true whether the geoscientist works with rocks, minerals, or water. Thus, one important goal of most quantitative laboratory analysis in the geosciences is to reduce the amount of error caused by contamination. Sample compositions, especially in geochemical analyses, are compared to standards, further complicating the determination of chemical composition. Data are only as good as the standards thus careful preparation is necessary to ensure that the standards and samples are not contaminated in the process of mixing, collection, or analysis. The elimination of contamination requires mindful attention to detail in every step of the research process.

The mindfulness that results in attention to detail requires practice. It develops with maturity not seen in most undergraduates (or even graduate students), perhaps because they have never had to practice mindfulness. Generally, we do not teach techniques classes in the geosciences, perhaps because of the diversity of quantitative

techniques found in our field. Thus, students are most likely to learn the consequences of failure to pay attention to detail during the research experience. This is not to say that faculty are immune to making errors. The difference is that the faculty member has the experience and humility to go looking for errors. When working with undergraduates, the faculty mentor must be prepared to recognize when and where analytical problems might arise, and how to avoid contamination problems in the first place.

The integration of river studies, including chemical analysis, into class projects have been described in the past (Cordua, 1983; Carlson, 1999; Dunnivant et al., 1999), as well as specialized sampling techniques (e.g., Browne and McAloan, 1998). The focus of this paper is how to avoid sample contamination when collecting and filtering river water samples for chemical analysis in the research setting. The first part of the paper describes where contamination can occur during sample collection and processing, the second details how proper technical skills help avoid sample contamination. The third part of the paper details the critical thinking skills used to detect sample contamination. These techniques are rarely taught as part of a class field exercise because of time restrictions, but are critical for executing sound scientific research. Examples and data are drawn from experiences with summer research students at Furman University. Although this paper uses the geochemical analysis of surface waters as an example, the concepts developed here are applicable to all types of geochemical analyses.

POINTS OF CONTAMINATION

Sample contamination is an issue in geochemistry because samples are of unknown composition. Therefore, proper techniques for sample collection and processing are important because the detection of sample contamination can be difficult. What is surprising for water sampling is the large number of points of contamination. The primary consideration is the type and level of contamination to worry about.

Although all water samples need to be handled properly, the worry of contamination depends on both the nature of the research and the nature of the river being sampled. For example, the study of trace element concentrations in rivers is difficult because concentrations are often in the range of parts per trillion (e.g., Shiller and Boyle, 1985; Shiller and Boyle, 1991). As a result, problems of contamination have been recognized and special techniques for handling and processing samples have been designed to avoid any source of contamination (Horowitz et al., 1992; Horowitz et al., 1996; Shiller and Taylor, 1996; Benoit et al., 1997). Because of the specialized nature of trace element analysis, these techniques will not be considered further. The techniques discussed in this paper, however, are applicable as the first step towards trace element analysis. In contrast to trace elements, the study of major element concentrations is often an issue of the rock type being drained. Carbonates and other sedimentary bedrock typically have soluble minerals and high total dissolved solids (e.g., Sarin et al., 1989). Igneous and

metamorphic silicate rocks, however, typically have less soluble minerals and lower total dissolved solids (e.g., Gaillardet et al., 1999). As a result, samples collected from rivers draining igneous and metamorphic rocks are far more susceptible to significant contamination that changes the composition of the sample. The students involved in the summer research project at Furman University over the last two summers have been collecting samples from the Enoree River basin. The Enoree River basin drains an area of 1863 km² in the Inner Piedmont province of South Carolina. The underlying rock types are predominantly high-grade granitoid gneisses, granite plutons, schists, and minor amphibolites in a thrust and fold belt. The lack of soluble minerals associated with sedimentary and volcanic rocks results in river water that is very dilute (specific conductivity is often less than 100 μS/cm) and therefore sensitive to contamination during sampling and processing. The collection and processing of samples for major element chemical analysis has three points of contamination.

The first point of contamination is the sample bottles. Theoretically, this is avoided by purchasing pre-cleaned high-density polyethelyne (HDPE) bottles and using the bottle only once before disposal. For most research programs, this approach is neither financially viable nor environmentally ethical. Therefore, sample bottles must be properly washed before reuse (Table 1). Improper rinsing after washing can cause the washing process itself to be a source of contamination. Although 8 M nitric acid is generally used for cleaning bottles (Eaton et al., 1995), 1 M nitric acid is safer and acceptable when low parts per billion or parts per trillion trace element concentrations are not routinely measured. Improper rinsing of the bottle after either washing step, however, can lead to contamination of the bottle. Detergents that are trace-metal- and phosphorus-free are the best choice for bottle washing. These detergents do contain sodium, however, so the tap water rinse is very important to eliminate sodium contamination. In areas where tap water is hard or contains high total dissolved solids, the tap water itself can be a source of contamination. Rinsing after the acid wash is also important because all of the nitric acid and tap water must be removed from the bottle using deionized water.

The second point of contamination is sample collection. Samples can be contaminated in two ways during collection. First, improperly cleaned sample bottles can be a source of contamination. Assuming that the sample bottle has been properly cleaned, handling of the bottle during sample collection can also lead to contamination. For example, fingers placed in the cap or bottle during or after sample collection can lead to contamination. This is especially likely just after breakfast or lunch when salty foods, such as potato chips, are eaten. Because sodium and chloride concentrations in dilute streams are often less than 3 mg/L, a small amount of salt added to the sample can lead to significant contamination. Clean hands and keeping fingers out of the inside of the cap and bottle are critical to avoiding sample contamination. Smoking during sample collection is also a problem as ashes that drop into the sample are a significant source of contamination. After

1. Empty contents of bottle and rinse with tap water.

2. Remove writing on bottle using a paper towel and methanol.

3. Wash inside and outside of bottle and bottle cap with bottle brush using a phosphate-free detergent.

4. Fill bottle with tap water, cap, shake well, and empty. Repeat this step three times.

5. Fill bottle with about a centimeter of 1 M HNO$_3$, cap bottle, shake well, and empty.*

6. Fill bottle with approximately 100 mL of deionized water, cap, shake well, and empty. Repeat this step three times.

7. Lay bottles and caps on side to dry. Cover with paper towels to prevent dust accumulation. Cap when dry.

*This step is omitted for bottles used to collect filtered samples for anion analysis.

Table 1. Procedure for washing a bottle.

sample collection, samples must be placed on ice while in the field and once returned to the laboratory stored in a refrigerator at 4°C until filtering to avoid bacterial activity. Although this is not strict "contamination," the activity of microbes can change the composition of the sample, particularly nutrient concentrations.

The third point of contamination is the filtering process. Samples are filtered through a 0.45 micron membrane filter in the laboratory using a positive pressure filter apparatus. An inert gas, such as N$_2$, is used to avoid contaminating the sample with carbon dioxide (if compressed air were used) and affecting alkalinity titrations. During the filtering process samples can be contaminated in three ways. First, samples can be contaminated by improper handling of the filter apparatus, filters, and collection bottles. As in the field, clean hands are a must and touching the inside of the bottles, the filter surface, or the inside of the filter apparatus can result in contamination. Second, the two bottles that are used for collecting anion and cation aliquots must be initially clean. Third, cross contamination can occur if the filter apparatus is not thoroughly rinsed with deionized water between samples to remove all traces of the previous sample, both water and suspended solids.

AVOIDING CONTAMINATION

The previous discussion clearly shows that there are numerous ways to contaminate a water sample. Avoiding contamination involves the student developing a set of technical skills and employing a degree of patience. Training sessions in the beginning of the summer introduced the students to the points of contamination and the proper sampling, filtering, and washing techniques. Close supervision of the initial sampling events reinforced what was learned during training and helped develop technical skills. The three techniques that reduce contamination are proper handling, proper rinsing, and pre-contamination.

As proper handling is nothing more than "clean hands, fingers out, no smoking," this discussion will focus on the latter two techniques.

Proper rinsing and pre-contamination involve the concept of "one million times dilution." The goal is to dilute any contaminant to a concentration far below the method detection limit of the analytical instrumentation used to determine the chemical composition of the sample. In the first point of contamination, sample bottles must be properly rinsed after washing with detergent and rinsing with nitric acid. A one million times dilution is reached by rinsing the bottle three times with at least 100 mL of tap water each time after the detergent wash and at least 100 mL of deionized water each time after the acid wash ($100^3 = 1,000,000$). This is particularly important after the nitric acid rinse. A 1 M nitric acid solution contains 62 grams of nitrate per liter of solution. Therefore, if only 1 mL (about one large drop) of 1 M nitric acid solution is left in a 250 mL bottle used for anion analysis, the result will be a concentration of 0.25 mg/L. The results of a brief experiment show the extent of possible contamination. Four students each washed a set of three 250 mL HDPE bottles. The first bottle of each set was not rinsed with deionized water following the nitric acid wash, but each bottle was shaken to remove as much of the nitric acid out as possible. The second bottle of each set was "thoroughly" rinsed with deionized water using a squirt bottle. The third bottle of each set was properly rinsed following the procedure in table one. All bottles were then filled with deionized water and analyzed for nitrate concentrations. The bottles that were not rinsed had concentrations of nitrate ranging from 13 to 135 mg/L, indicating that even after shaking, far more than 1 mL of 1 M nitric acid was left in the bottle. The bottles rinsed with a squirt bottle had nitrate concentrations ranging from 1 to 12 mg/L. Of the bottles washed according proper procedure, only one of the four had a nitrate concentration above the detection limit. Because even proper procedure can result in some

nitrate in the bottle, we had students wash anion bottles separately and eliminated the acid rinse step for these bottles. This process was simplified by using different sized bottles for different purposes. A 500 mL bottle was used for collecting samples in the field, whereas cations were filtered into a 125 mL bottle and anions were filtered into a 250 mL bottle. Bottles were grouped for washing, so that the nitric acid rinse could easily be avoided for the anion bottles. If a mistake is made, the one million times dilution should avoid a contamination problem.

In the second point of contamination, pre-contaminating the 500 mL sample collection bottle and cap by rinsing three times with river water is effectively a one million times dilution of anything that may be left in the bottle. The pre-contamination step is a check against any mistake made in washing the sample collection bottles used in the field. To reemphasize, however, this does not eliminate contamination cause by improper handling of the sample bottle with dirty hands or smoking.

The third point of contamination, sample filtration, is perhaps the most sensitive point in the process. Cross contamination is avoided by thoroughly rinsing the filter apparatus with tap water to remove mineral and organic debris, then thoroughly rinsing with deionized water. Because the filter apparatus can't be easily "filled" three times, three separate thorough rinses with a squirt bottle has to work as a "one million times dilution." This rinsing procedure is followed by pre-contamination with the sample to be filtered. The pre-contamination step is the weakest point and most susceptible to contamination. Pre-contamination involves rinsing the filter apparatus with about 50 mL of sample and collecting the filtrate into the cation and anion sample collection bottles, or approximately 25 mL per bottle. The bottles are capped, shaken, and the water is discarded. The rest of the sample is then poured into the filter apparatus, filtered, and collected. The small amount of sample used for pre-contamination in this procedure relies on the sample collection bottles having been properly washed because a one million times dilution is not possible. Problems with nitrate contamination are in part avoided because nitric acid is not used to wash the anion collection bottles. Using larger volumes of sample is impractical because it will often clog the filter. Furthermore, material collecting on the filter effectively changes the filter pore size and leads to overloading of the filter (Horowitz et al., 1996), so as small a volume of sample as practical should used for pre-contamination. Generally, a 500 mL sample is enough for pre-contamination and the collection of enough filtered sample for the replicate analysis of anion and cation concentrations and alkalinity. Alternatively, a larger sample could be collected, and two filters could be used. The first filter would be used to properly pre-contaminate the two bottles, and the second filter would be used to actually collect the sample after it had been pre-contaminated. For large numbers of

samples, however, the use of two filters is not time efficient or economically viable.

Training sessions in the beginning of the summer introduced the students to the points of contamination and the proper sampling, filtering, and washing techniques. At the same time, however, students are also learning how to properly calibrate, use, and maintain the pH meters, conductivity meters, and dissolved oxygen meters used in the field. They also are learning or relearning some basic analytical techniques used in the laboratory such as how to use a pipette, mix 1 M nitric acid, and perform alkalinity titrations. The techniques taught along with the introduction to the research topic and project design. As a result, the students undergo a very steep learning curve, so the most important aspect of the training is the availability of the faculty to answer questions and coach students through the various techniques. During this time, the students are moving from the classroom mentality where mistakes are penalized to a research laboratory mentality where mistakes need to be caught and rectified.

The training process for sample collection, filtration, and bottle washing was divided into two parts. Students were first shown the various laboratories and methods in a show- and-tell manner. This included demonstrations of sample collection, filtering, and cleaning techniques. This allowed the faculty members to gain an understanding of how many of the students had previously used the various techniques. As an example, almost none of the students in the last two years have ever operated a high-pressure gas tank like the one we use for our positive filtration apparatus. Therefore, some of the training time is devoted to issues that are simple, but very important. Students then were taken to a lake on campus to practice collecting a sample and using field instrumentation. Samples were collected, bottles labeled, field notes written, and samples were placed on ice and returned to the laboratory. At that time, the samples were filtered then the bottles were washed. Close supervision of the initial research work reinforced what was learned during training and helped develop technical skills.

Observations of students over the last two summers indicate that bottle washing and filtering tend to be rushed more as the summer progresses. These methods require patience and precision, so faculty mentors provided reminders to be patient and methodical. For bottle washing, most often the problem is improper rinsing of the bottles after the nitric acid wash. This problem occurs in two ways. First, the bottles may not be rinsed to the specified one million times dilution with deionized water because too little water is used (e.g., using a squirt bottle to rinse or only rinsing once). Second, the bottles may not be rinsed with properly deionized water. Students must learn that the deionization process is completed by an ion exchange reaction that takes time; the process is not simply filtration. One mistake observed as a result of this mis-

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understanding was leaving the deionized water tap on continuously rather than using small amounts of water. A five-gallon reservoir can help this situation, and once an hour about a gallon of water was added to keep the reservoir relatively full and to ensure that the water was properly deionized. On occasion, however, faculty members entered the lab to find the deionized water tap running continuously into the reservoir and the tap of the reservoir open continuously to wash bottles. The result was nearly the same as rinsing the bottles with tap water. The students simply did not fully understand how the deionization process works, assumed it was a filtration system and wanted to speed up the bottle washing process. Conversely, the faculty did not make the process clear enough to the students and did not provide timely reminders.

All of the above methods of avoiding contamination are relatively simple, but require constant attention on the part of the student. This relates to the introductory statement about "mindfulness." Part of the research process in geochemistry, as in other fields, is developing the self-discipline to complete a tedious task properly. This is an acquired skill that requires much practice and a depth of understanding of the consequences of improper attention to detail. Observation of students over that last two summers suggests that no amount of pre-research training will develop this skill and that the student must be constantly reminded of the importance of the collection, filtration, and washing processes to the integrity of the data throughout the summer.

## METHODS OF DETECTING CONTAMINATION

Although the methods of sample collection, filtration, and the bottles are designed to eliminate sample contamination, poor practice of the methods can result in contamination. Detecting contamination involves the student developing critical analytical skills and developing interpretation skills. The three checks for contamination are procedural blanks, collecting duplicate samples during a single sampling event, and collecting multiple samples over time at a single location. Generally, student understanding of the importance of detecting contamination improves over the course of the summer, and initially the development of a routine procedure for the collection of procedural blanks and duplicate samples ensures that these samples are actually collected. A general requirement was that the first sample of the week be collected in duplicate and that the first day of sampling include a blank (samples are collected twice a week). Of course, the difficulty is making sure that the students remember to actually collect the samples. In order for these types of samples to be useful, they must be collected using the same procedure as for any other sample. Clearly, the goal of quality control samples is to determine the presence of contamination. Detective work is then required to determine at which step in the process contamination occurs.

Procedural blanks are simply a sample collection bottle filled with deionized water at the beginning of the day, carried into the field and back, and then filtered with all the other samples. The procedural blank must be treated like any other sample, and should be properly pre-contaminated with fresh deionized water. As deionized water should contain no solutes above detection limits, the sample functions as a "blank." Any solutes in the sample will reveal contamination originating somewhere in the process of sampling, filtration, or washing. The collection of a blank is more difficult than it sounds. As an example, during the summers of 2000 the students collected 20 procedural blanks. Of the five cations analyzed, only silicon concentrations were above method detection limits, and only towards the end of the summer. This was the result of a failed carbon filter on the deionization system. Of the seven anions analyzed, only chloride, sulfide, and nitrate were found to be above instrument detection limits in blanks. Chloride was the worst offender, appearing in fifteen of the blanks with an average concentration of approximately 0.4 mg/L. Sulfate and nitrate appeared in 5 and 10 blanks, respectively and had respective average concentrations of approximately 0.4 and 0.1 mg/L. The results of the procedural blanks for summer 2000 were then compared to the results of forty-three analytical blanks to help determine if contamination is the cause of the blank compositions. The presence of chloride was detected in less than half of the analytical blanks at an average concentration of approximately 0.3 mg/L. Sulfate and nitrate were detected in less than ten percent of the analytical blanks at respective average concentrations of 0.3 and 0.1 mg/L. The twenty-six procedural blanks collected during the summer of 1999 give similar results.
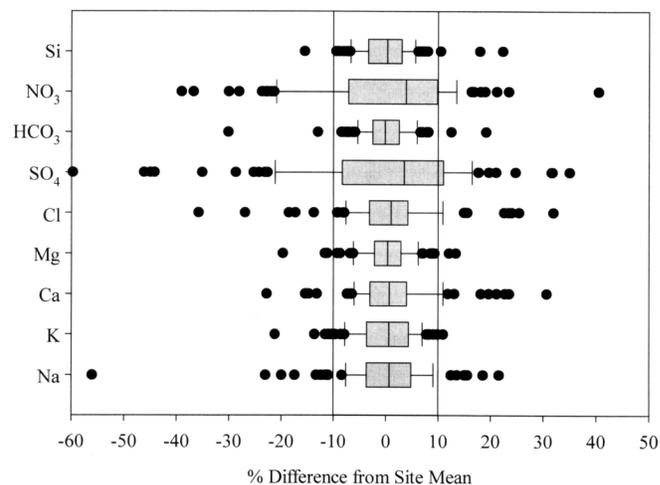
The similarity of the concentrations between the procedural blanks and the analytical blanks suggests that the procedural blanks were not properly pre-contaminated with fresh deionized water. Investigation of student procedure through informal interviews revealed that blanks were often collected from the deionized water reservoir rather than fresh from the deionized water tap. The washing procedures described in the above section suggest that such water wasn't always truly deionized because of improper use of the water polishing system. Other possibilities for procedural blank problems include cross-contamination and poorly washed bottles. However, the washing experiments described above indicate that improperly washed bottles would result in much higher concentrations of nitrate, if the anion bottles were mistakenly rinsed with nitric acid. Cross contamination should have led to contamination by both chloride and sulfate for all samples, which did not occur.

Duplicate samples are used as checks for contamination and precision. Because rivers are flowing and may or may not be turbulent, the chemical composition of the river can vary over both time and space. As a result, duplicate samples may also vary in composition. This leads to the question of grab samples versus time and space integrated samples, which is beyond the scope of this discussion. The summer research program used the grab sample method common to many studies of large rivers where lack of turbulent mixing is a greater problem than for the small streams in this study (e.g., Sarin et al., 1989;
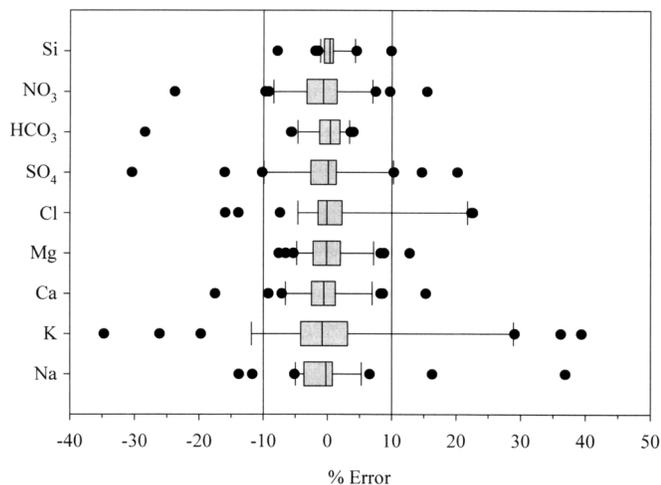
Figure 1. The percent error for thirty-two duplicate analyses collected during the summer of 2000. The majority of the errors are less than 5%. Most of the positive outliers are associated with a sample location downstream of a sewage treatment plant. Large differences between duplicates can be an indication of sample contamination.

Figure 2. The percent difference of samples from site means for fifteen localities in the Brushy Creek watershed collected over a seven week period (n = 105). Brushy Creek is one of four watersheds in the Enoree River basin sampled during the summer of 2000, along with the Enoree River itself. The percent difference is calculated in the same manner as percent error in figure 1. The data indicate the inherent temporal variability in the composition of river waters. The majority of the data, however, fall within 10% of site means.

Huh et al., 1998). Theoretically, however, duplicate samples should be very close in composition. The data for thirty-two duplicate samples collected in the summer of 2000 indicates that this is generally the case. The vast majority of the duplicate samples are within 10% of the theoretical concentration ratio of one to one (Fig. 1). Errors greater than 10% often either are associated with samples that have very low concentrations of a particular element, elements that are hard to measure accurately, or samples with charge balance problems. Examples include nitrate, potassium, and chloride, respectively. Duplicate analyses can also be used to calculate analytical precision (Eaton et al., 1995). The precision was in general very good. Sulfate, nitrate, magnesium, potassium, calcium, and silicon analyses had a precision of 0.30 mg/L or better. The precision of sodium, bicarbonate, and chloride analyses were 0.45 mg/L, 0.79 mg/L, and 1.15 mg/L, respectively. Bicarbonate has the highest concentration of the anions, averaging nearly 40 mg/L, so the analytical precision is reasonable. The relatively poor precision of sodium and chloride is skewed by six sets of duplicate samples collected at a location downstream of a sewage treatment plant. Five of the six duplicate samples have large differences between sodium and chloride concentrations. Removal of these samples improves the analytical precision to 0.30 mg/L for sodium and 0.14 mg/L for chloride. These samples account for many of the outliers for each solute in figure one as well. Based on the analytical precision, differences greater than 0.30 mg/L between duplicate samples suggest potential contamination problems. Again, the results from the summer of 1999, when seventeen duplicate samples were collected, are similar for both the precision and error analysis.

As an additional check, each sample locality was sampled seven times during the summer. Even under normal base flow conditions, concentrations do vary from week to week, particularly for nitrate and sulfate (Figure 2). The range of variation, however, is generally small. Therefore, any major change in solute concentrations is suspect if it cannot be accounted for by stream observations (e.g., foam on the stream or changes in discharge). Determining whether the change in concentration for a particular solute is because of contamination or because of natural variation is difficult and requires thoughtful analysis.

Students had to be trained to look for inconsistencies in the data. Most often, faculty members had to point out suspect data to the students and explain the significance of the problem. Interpretation of the results is very time consuming and difficult. In most cases, proving contamination is generally very difficult. As a result, the best safe guard is for the student to be able to trust his or her own technique and be constantly mindful in their work.

SUMMARY

The study of rivers provides many excellent advantages for undergraduate research. In areas other than deserts, rivers are nearby and easily accessible. Numerous research topics in geochemistry are pertinent to rivers, from applied environmental research to basic geochemical research. Water samples are relatively easy to collect and analyze compared to rock samples, allowing the develop-

ment of a large, interpretable data set during a short summer research season. Most undergraduate students, however, have not been exposed to the research level techniques associated with sample collection and processing. In geochemistry, contamination is a constant concern because the samples have unknown composition. The concept of mindfulness, the ability and discipline to focus only on the current task is critical for the collection of an uncontaminated sample. This skill, however, requires practice.

Student research in fluvial geochemistry gives ample opportunities to develop analytical, laboratory, and critical thinking skills. Many of these skills can be developed independently of the specific research project because the technique of collecting an uncontaminated sample requires these skills. Avoidance of contamination is not difficult in theory, but requires mindful attention to detail in the practice of seemingly inconsequential and tedious tasks such as bottle washing, sample collection, and filtration. Interpretable data requires the student to develop a data set with integrity, which in turn requires the growth of intellectual maturity and discipline. Success of the student during a summer research experience in large part depends on constant teaching, patience, and encouragement by the faculty mentors.

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