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THE ELEMENTARY COURSE IN A CHANGING MINERALOGY[1]

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At the Copenhagen meeting of the International Mineralogical Association, a Commission on the *Teaching of Mineralogy* was established. The first meeting of the Commission was held in Washington, D. C. in April 1962. At that time, one of the principal items of discussion was the beginning course in mineralogy. How many hours are devoted to it in lecture and laboratory? What is its scope and content? How many minerals are studied? What is the average age of the students? These and many other related topics were considered. Most of the members of the Commission had ready answers and could speak with authority regarding the manner in which mineralogy is taught in their respective countries.

As the representative from the United States, I was at a loss for answers and could only guess at the content of the average course in the United States. I know my American colleagues well enough to realize they are an independent group. The mere knowledge of the content of my own course in no way makes it possible for me to predict the content of theirs. Moreover, according to the American Geological Institute Report of 1962, the number of institutions teaching some mineralogy is large, 228, and the time devoted to the beginning course varies greatly.

In the hope that I could speak with more authority at the next meeting of the Teaching Commission, I sent out a questionnaire early this year to the 228 institutions teaching mineralogy in the United States. I am sure that many of you here received one and to those who completed it, may I express my thanks. Knowing the almost universal dislike for filling out questionnaires, I felt a fifty per cent return would be good. I was, therefore, delighted to have 25 per cent returned by the end of one week and 72 per cent returned by the end of the second week! Altogether, there has been a 93 per cent return.

[1] Address of the retiring President of the Mineralogical Society of America at the 44th annual meeting of the Society at New York, New York—November 19, 1963, Mineralogical Contribution No. 410 Harvard University.

The rapidity with which the questionnaires were returned, the care with which they were completed, the many unsolicited comments and letters, and the almost universal request by the respondents that they be informed of the results, indicated that interest in the teaching of mineralogy is great. Accordingly, I decided to use the data obtained as the basis for my talk to you this afternoon.

Concern over the teaching of an elementary mineralogy course is not new. Since 1950, largely through the efforts of the Association of Geology Teachers, many thoughtful papers on various aspects of the subject have appeared in the *Journal of Geological Education*. In March, 1956, a symposium on the *Teaching of Elementary Mineralogy* was held at West Virginia University, and the results published in the *Journal of Geological Education* later that year. More recently (June, 1961) a workshop was held at the University of California at Davis to evaluate the elementary courses in mineralogy as taught in California and to make recommendation regarding their teaching. A report summarizing the results of this workshop was issued by the California State Department of Education (1961). Those of you familiar with these papers will discover shortly that I am sympathetic to most of the ideas presented in them.

Results of the Questionnaire

Let us first consider the results of the questionnaire which give a generalized idea of the present-day mineralogy course. We learn that mineralogy is taught by Departments of Geology or Mineralogy and for Geology students. The only two exceptions are one Department of Ceramic Engineering and one Department of Science. Although it is largely students of Geology who take these courses, many institutions draw students from other disciplines. In order of decreasing numbers they are from chemistry, metallurgy, physics, agronomy, ceramic engineering and a scattering of others.

Some of the larger and more technical institutions offer two or three courses of beginning mineralogy each slanted to a different group of students. When more than one course is offered, the most comprehensive is for the geology majors.

From the answer to the question "What has been the average number of students taking the course during the past five years?", we find that classes are not large. The number of students varies from 1 to 160 but the median is between 10 and 11 (Fig. 1). Most of these students are Sophomores and Juniors with virtually no Freshmen and only small numbers of Seniors and Graduates.

For those institutions answering this question, the combined total of students taking mineralogy has averaged 2,550 a year for the past five years. Extrapolating to include both those institutions not answering this particular question and those not returning the questionnaire, we arrived at a figure of nearly 3,100. Thus, in the United States at the college level, more than 3,000 students a year are introduced to the subject of mineralogy.

There is a great variation in the amount of time devoted to the beginning course which ranges from one quarter to over an academic year. The elementary course is covered in one quarter by 10 per cent of the institutions, one semester by 51 per cent, two quarters by 7 per cent and a full

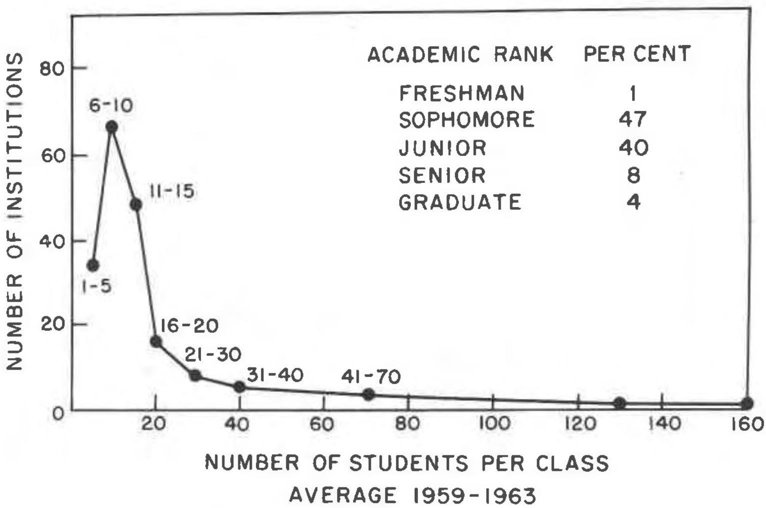

FIG. 1. Number of students per class. Average for years 1959–1963.

academic year, two semesters or three quarters, by 31 per cent. However, these figures are not meaningful unless considered in conjunction with the number of hours of lecture and laboratory. For example, some one quarter courses have more hours of instructions than some two semester courses (Fig. 2). In each of the four groups, the maximum number of hours of instruction is well over twice the minimum, and in three of the groups the maximum is over three times the minimum. Thus for the beginning course in mineralogy hours of instruction vary from 30 to over 250. The median is 90 contact hours.

About one third of the institutions conduct field trips that are required and another third offers optional field trips. Although there are many exceptions those courses having the greater number of hours of lecture and laboratory tend to have field trips, thus further increasing the disparity between the amounts of instruction.

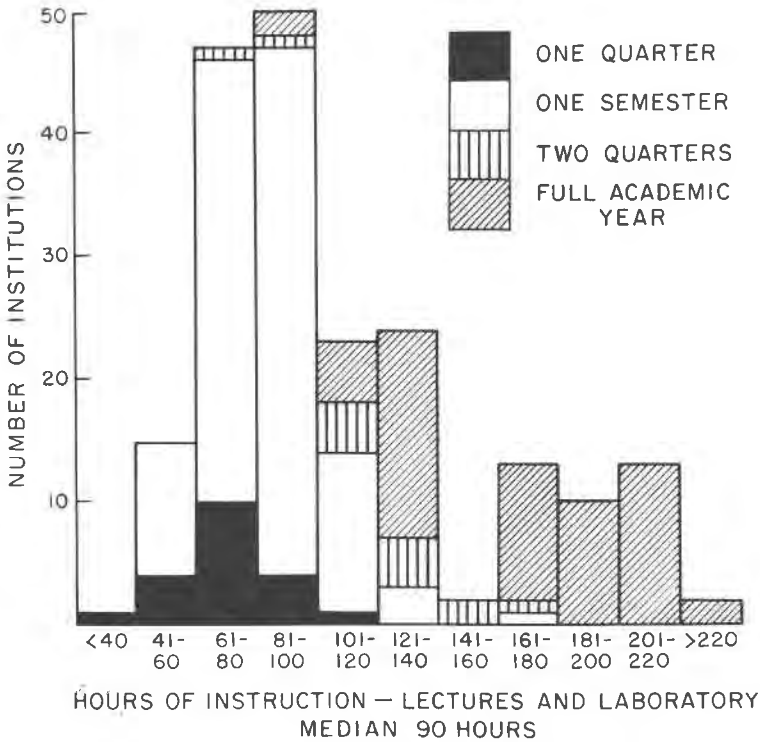

FIG. 2. Hours of instruction—lectures and laboratory. Median 90 hours.

Answers to specific items on the questionnaire are as follows:

Blowpipe Tests	
Are they used?	Yes—63; No—37 per cent
Wet Chemical Tests	
Are they used?	Yes—53; No—47 per cent
Prerequisites	
Chemistry?	Yes—81; No—19 per cent
Geology?	Yes—60; No—40 per cent

At 66 per cent of the institutes, at least one year of college chemistry is prerequisite; another 15 per cent require lesser amounts. The traditional links of mineralogy with geology and chemistry, seem, on the whole, to be preserved. However, it is surprising that nearly half of the institutions use no chemical tests.

How many minerals studied?

The number of minerals reported as mentioned in lectures has little relation to the number of quarters or semesters or to the hours of lecture.

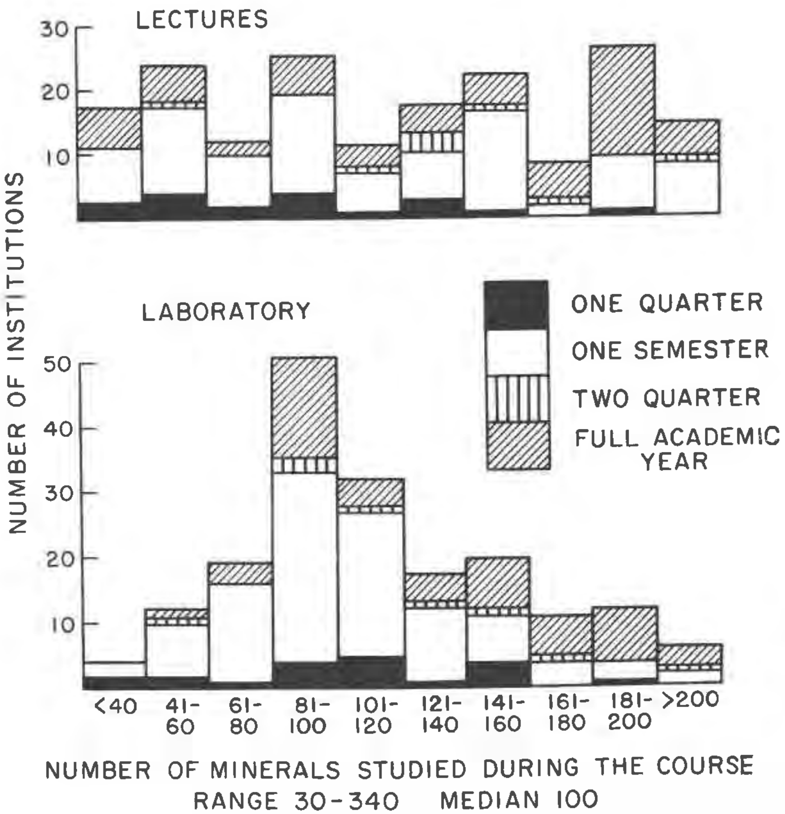

FIG. 3. Number of minerals studied during the course. Range 30–340. Median 100.

Furthermore, over 10 per cent of the returns gave no figure for the minerals considered in lectures. More significant is the number of minerals studied in the laboratory where specimens can be handled and their properties determined. Of the minerals reported studied in the laboratory, the highest figure was 340, the lowest 30 and the median approximately 100 (Fig. 3).

All but 2 per cent of the courses use a standard textbook. Although I would have been greatly interested in the answers, I refrained from asking "Which textbook?" Twelve per cent use a separate laboratory manual; and 56 per cent use determinative tables for mineral identification.

Extent of use of crystal chemical concepts	*Per Cent*
Chief basis for descriptive mineralogy	40.5
Use extensively.	45.0
Is introduced as a separate topic.	14.0
No use made.	0.5

It thus is apparent that the plea in 1956 by the National Association of Geology Teachers for the wider use of crystal chemical concepts has been heeded, and that mineralogy is largely taught on a foundation of these ideas.

Crystallography

Morphological Crystallography is an integral part of 94 per cent of the elementary mineralogy courses. In 3 per cent of the institutions, a separate course in crystallography is offered as prerequisite to mineralogy and at only one per cent of the institutions is crystallography completely omitted.

The hours of lecture and laboratory concerned with morphological crystallography vary greatly (Table 1). In general the fewer the hours devoted to the whole course, the higher the percentage of the time devoted to crystallography. Apparently most instructors are willing to sacrifice other aspects of mineralogy to include a certain minimum of crystallography.

Table 1. Time Spent on Morphological Crystallography

	Lecture Hours			Laboratory Hours		
	Range	Average	% Time	Range	Average	% Time
One Quarter	0–15	8	26	4–40	13	29
One Semester	0–24	10	27	0–48	15	28
Two Quarters	3–24	13	23	4–30	21	24
Full Year	2–28	14	19	0–96	26	19

Considering all the courses, the median is 11 hours of lecture and 13 hours of laboratory for crystallography. Since the median for the course as a whole is 90 contact hours, crystallography consumes about one-fourth of the time. From Table 1. we see also that the average percentage of time spent on crystallography is about 25.

Symmetry

Are students held responsible for its recognition? Yes—99; No—1 per cent

Hermann-Mauguin Symbols

Are they used? Yes—63; No—37 per cent

Crystal Classes

How many classes are covered? The number of crystal classes considered varies from 2 to 32, the median being 15. However, in one-third of the courses, all the 32 crystal classes are covered.

Designation of crystal forms

By name only—4 per cent
By Miller indices only—5 per cent
By both name and Miller indices—91 per cent

Krantz wooden models or equivalent

Are they used?	Yes—98; No—3 per cent
Are they used exclusively?	Yes—7 per cent
Supplemented with natural crystals?	Yes—91 per cent

Crystallography Laboratory Manual

Is a separate manual used?	Yes—10; No—90 per cent

Interfacial angles

Are they measured?	Yes—70; No—30 per cent
How are they measured?	

Contact Goniometer—61 per cent; Optical goniometer—9 per cent.

Crystal Projections

Do students make them?	Yes—56; No—44 per cent
Type of projection?	Stereographic used by nearly all but the gnomonic is introduced by a few.

Structure models

Are they used?	Yes—82; No—18 per cent
Do students construct them?	Yes—29; No—71 per cent

X-ray techniques and principles

Are they introduced?	Yes—73; No—27 per cent
Are photographs or strip charts interpreted?	Yes—25; No—75 per cent

Optical crystallography

Is it introduced?	Yes—44; No—56 per cent

In approximately 25 per cent of the courses, both thin sections and immersion techniques are discussed.

The "Average" Course

After reviewing the results of the questionnaire, we can say with considerable assurance what was suspected at the beginning; there is no uniformity to the elementary mineralogy course. Had some questions been phrased differently or others asked, the results possibly would have been more meaningful but certainly not more uniform. If we take what the majority does as being average, this course can be summarized as follows:

It is a one semester course with two lectures and four hours of laboratory a week taught to 10 Sophomore and Junior geology students. With a prerequisite of chemistry, crystal chemistry is extensively used as a basis for descriptive mineralogy. Blowpipe and wet chemical tests are used for the study of 100 mineral species. Determinative tables found in standard textbooks are used for mineral identification.

About one-fourth of the course is devoted to crystallography. In the study of crystal morphology wooden models and natural crystals are used on which interfacial angles are measured with a contact goniometer and then projected stereographically. International symmetry symbols are use, fifteen crystal classes are considered, and forms are indicated by both names and Miller indices. In considering the structure of crystals, structure models are used and x-ray techniques and principles are discussed.

This then is the "average" course; but is it the best course? Of all the many branches of the geological sciences, mineralogy is probably the most fundamental. In their specialized areas the petrologist, the economic geologist, the geochemist, the sedimentationist are all practicing mineralogists. The structural geologists, the geomorphologists and the geophysicists are also concerned with minerals and the way they respond in various physical and chemical environments. Frequently the only mineralogy *per se* to which these specialists have been exposed is the elementary mineralogy course. Does a one semester course of 90 contact hours permit sufficient time to build an adequate mineralogical background? I believe it does not, particularly if we are to allow some time to make excursions into other fields. This is desirable not only to point up the dependence of mineralogy on other disciplines but also to demonstrate mineralogy's contribution to them.

What Should We Teach?

The excellent course as taught a generation ago will not be even a good course to-day unless new material has been added. As the science grows, we must grow with it. But if we add material as it comes along, something of the old must go if the time available for presentation remains the same. Much that is old is still good and we must not omit it merely because it is old. On the other hand, we should not add material merely because it is new. Each new technique, concept, and idea should be carefully weighed and the question answered—Will it add more to the overall understanding of minerals than the old material sacrificed to permit its introduction?

From the results of the questionnaire, it appears that the teachers of our "average" course have made an effort to maintain this balance. Some, I feel, still teach the course of thirty years ago with little change. This is done by a few as the result of considered judgment; they are convinced this is the best course. A larger group, I believe, teach a course as was taught them because it's the most effortless way to do it. They may argue that the new concepts are much too advanced for the elementary student. In many such cases, if the instructors were honest with themselves, the answer would be that the concepts are too advanced for the instructors. The beginning student has no basis for comparison. Whatever is presented to him by his professor—This is Mineralogy.

At the other extreme, there is a small group of instructors who accept the idea that everything that is new is good and must be introduced into the elementary course at the expense of practically everything that is old. Their courses can scarcely be recognized as mineralogy. In a way, mineralogy is unique in being the meeting place of other sciences. Physical and chemical principles are used but the mineralogist should not try to outdo the physicist or chemist. The world will be the poorer if the mineralogist loses his identification with natural science and geology. As teachers of mineralogy it is our function and duty to preserve this relationship.

What should be included to-day in the elementary course? First, we should stress recognition and determination of the common minerals. This should be the core of every course and for it most of the old methods still have a place. To know the minerals one must handle them—as many as possible, examine them carefully, and glean all the information possible from them with pocket knife and hand lens. By the end of the course 100–150 minerals should be recognized as old friends by their physical properties or simple tests.

For 100 years the blowpipe has been a major tool for mineral identification. Although it has been abandoned in many institutions in favor of more sophisticated determinative methods, it is still used by the majority. This is good, for the blowpipe has not outlived its usefulness. It has a place in modern mineralogy that is not taken by the polarizing microscope or the x-ray camera. Minerals are chemical elements or compounds and their chemistry is their most important property. Thus for the beginning student, the blowpipe serves not only as an excellent determinative tool but keeps the chemistry constantly before him. For example, he learns that an unknown mineral is a sulfate containing strontium. When he tracks it down, it has been brought home to him that strontium sulfate is celestite. This is a much more rewarding experience than arriving at a name by looking up a series of numbers in a table that to the student has no relation to any of the obvious properties of the mineral. It is frequently the quickest method as well. If more advanced methods of mineral determination are used at an early stage, the student may come to rely on them so completely that he may never again look critically at the specimen he is trying to identify. The teaching methods should call attention to the easily observed properties, not obscure them. In this age of high speed computers, the student may feel he is using advanced methods if he can feed information into a machine and have the answer appear on the print-out. We should do this in a way. Feed the information into the computer—the student's head—and come out with the answer.

It is my firm conviction that traditional methods of mineral study should be used in the elementary course. If this is done, the student who has this as his only mineralogy will have been taught the fundamental properties that will enable him to recognize minerals in the field. And those intending to take more advanced courses will have established a firm foundation on which to base them.

There is no instructional substitute for observing minerals in the field in their natural environments. A plea for this was made by Landes in his Presidential address "Geological Mineralogy" delivered before the Mineralogical Society of America in 1945 (Landes 1946). More recently papers by Heald (1956) and Roy (1957) emphasize the desirability of this approach. The results of the questionnaire show that over one-third of the courses have neither required nor optional field trips. This is unfortunate, for only by seeing minerals in association with each other can the student gain a proper understanding of the interplay of the geological and geochemical processes that gave rise to them. It is here that he learns that mineralogy is not a completely separate segment of earth science, but is closely integrated with geochemistry, petrology, ore deposits, and sedimentology. Whether or not minerals can be seen in the field, they should not be studied as isolated phases but rather in associated suites. This is not only valuable from the paragenetic viewpoint, but also as an aid to identification. We recognize minerals, as we do people, by the company they keep.

The approach to crystallography to-day is and should be different from that of 50 years ago since so much has been learned regarding internal structure. Nevertheless, the study of crystal morphology need be little changed. On the basis of symmetry, crystals classes should be defined and grouped into crystal systems. Forms should be named and Miller indices assigned to them. The use of well-formed crystals in mineral identification should be stressed.

In spite of the fact that crystallography is an exact science, it has at the elementary level been treated in a qualitative manner. There is an increasing tendency, and quite properly so, to make it more quantitative. The proportion of students who are measuring and projecting crystal angles and using them to calculate axial ratios is much higher today than formerly. The reason for this is not merely to put more rigor into the course, but now an axial ratio, calculated from morphological measurements can be compared with the structural axial ratio. This comparison usually shows them to be in good agreement and brings home to the student the fact that the faces and angles between them are the outward expression of the structure.

In teaching elementary crystallography, it is important that the most generally accepted names and symbols be used at the beginning. These are, for the names of the crystal classes, those proposed by Groth; and for symmetry, the international symbols. Oversimplification and overgeneralization is not a kindness. If this is done and the student later undertakes a study of crystallography in a more rigorous manner, he finds he must unlearn a great deal.

There is much that the elementary course includes or should include that was not taught a generation ago. This material is more concerned with ideas leading to a fundamental understanding of the properties of minerals than with methods and techniques. Most of these concepts derive from our increased knowledge of crystal structure and are embodied in the relatively new science of crystal chemistry. In them the student can discover most satisfying explanations of many of the problems that baffled mineralogists only a short time ago. Polymorphism, ionic substitution, and solid solution become meaningful. The relationship of the physical properties of specific gravity, hardness, and cleavage can be understood in the light of internal structure and chemistry. The classification of minerals, particularly of the silicates, is given logical explanation.

For the average student to grasp quickly the ideas involved in crystal structure and crystal chemistry, he should see and handle atomic packing models. Word descriptions and photographs are but poor substitutes for the models themselves. With a few well-chosen models, chemical bonding, ionic radii, ionic substitution, coordination, and structure-type are graphically demonstrated. Better still if time and materials permit, the actual construction of a simple structure-type model will fix these principles firmly in the student's mind.

According to the results of the questionnaire, nearly half of the courses taught in the U. S. make extensive use of crystal chemistry, and I am sure the students have a better understanding of mineralogy as a result.

When a student completes the elementary course, he cannot be considered a trained mineralogist. However, it is our duty and responsibility at even this early stage to try to interest the good student in mineralogy as a life work. In fairness to him we must point out the various opportunities for employment. Some, of course, will become teachers but teaching openings are becoming scarce in mineralogy. Most mineralogists in training must look forward to working for industry or in a private or government sponsored research laboratory. The student's first question, then, is likely to be, "What does a mineralogist do in such a capacity?" When we face this question squarely, we find that a high percentage of trained mineralogists are working on high temperature—high pressure phase equilibria, crystal growth, and mineral synthesis. Is it possible to introduce a little of each of these into the elementary course? I believe it is and without consuming too much time.

We probably cannot teach much about phase equilibrium diagrams, but we can demonstrate the inversion of one polymorphic form to another. For example, mercury iodide (HgI_2) melted (m.p. 259° C) on a microscope object glass will, on cooling, crystallize as the yellow orthorhombic form, which will invert at 126° C to the red tetragonal polymorph. Also, crystals can be grown without elaborate equipment following procedures similar to those outlined in *Crystals and Crystal Growing* by Singer and Holden (1960). Crystal growing projects can be assigned to be carried out on the student's own time with a report on his findings due at the end of the term.

High temperature—high pressure synthesis is more difficult but it can be done as a demonstration if a simple ladies bomb is available. The instructor can show the amounts of the various ingredients being weighed out, seal the bomb, and put it in the furnace. Toward the end of the term he can let the class see the opening of the bomb, view the results, and write a report on what happened. If the course is taught at a university where research in high pressure—high temperature synthesis is being carried out by graduate students or others, the problem is simplified for the instructor. Arrangements can be made for the class to visit the laboratory where the experiments are made and have the researcher conduct the demonstrations.

It is important that the elementary student be aware not only of the type of work a mineralogist does but also of the methods and instruments he uses in advanced study. At the appropriate times during the course, demonstrations or explanations should be given of magnetic and heavy liquid mineral separation and differential thermal analysis. The student should be introduced to the polarizing microscope and told of what can be accomplished with it by a person skilled in its use. Since the results of x-ray study have so revolutionized mineralogical thought, every student should be aware of them. He should not only be made conscious of their existence but also should be told what information can be obtained by using different methods. Little can be gained by having him use the instrument he doesn't understand. But he will benefit greatly from a demonstration of how it is used. The interpretation of strip charts or powder films will give him both a sense of accomplishment and a feeling of having been initiated into a technique that stands at the frontier of the science.

How Should We Teach?

I have outlined briefly what I feel should be taught in the elementary course. How to teach it presents a more difficult problem. Perhaps the best guarantee of the success of an instructor is his spontaneous enthusiasm for his subject. Minerals in the field and hand specimen are aesthetically pleasing and their identification is a stimulating challange to the student's ingenuity. The occurrence, extraction, and use of minerals is a fascinating human document. Thus to gain the student's interest it is necessary only for the instructor to avoid obscuring the intrinsic attractiveness of the subject by stuffy pedagogy. Many a good student has been attracted to the field by a fascinating course in elementary geology, only to be turned away by a poorly taught course in mineralogy. Elementary mineralogy can be made interesting without sacrificing quality; indeed, the quality can be enhanced by so doing.

A generation ago many mineralogy courses consisted largely of the memorization of isolated facts about different minerals. As a result they were dull and the student maintained an interest not because of the instruction but in spite of it. We are fortunate in that to-day we have in crystal chemistry an exciting approach to the subject as a whole. It serves as a unifying thread joining the many facts of descriptive mineralogy that often appear quite separate and unrelated. It not only ties together the properties of a single species but, as recently pointed out by Gillerman (1962), gives a new dimension to mineral genesis and association. Interest in any course can be generated by the early introduction of crystal chemistry concepts and maintained by their continued use.

Not all mineralogy courses taught by our elders were dull. We would do well to consider them, for many of the things that were stimulating to their students may be equally stimulating to ours. One of the great American teachers of mineralogy was Charles Palache. He was disappointed in the mineralogy course he took as an undergraduate. His personal notes say of it there was "nothing living about the subject; only models, formulae, and drudgery." He made certain that his own course would not be subject to the same criticism. Although his students were thoroughly trained in fundamentals, the lectures were enlivened in many ways. In addition to numerous anecdotes of his personal experiences, there were descriptions of famous localities, stories of discovery and development, genesis and association, and unusual mineral uses. I am sure there are many courses taught in the United States where the Palache or similar influence still exists, and mineralogy is made to come alive with the names of faraway places associated with the minerals found there and the men who found them.

Because there is so much that is desirable to include in the elementary mineralogy course, I feet that one semester with two lectures a week is insufficient time to present it. Increasing the lectures to three a week in many cases would permit introduction of new material while retaining the best of the old. If, however, the time can't be increased, something must go. What should be left out? This question has been answered differently by different instructors, but material omitted from the lectures need not necessarily be omitted from the course. Certain parts of the subject the student can learn on his own from the textbook and selected outside reading. I agree with Faust (1956) that under these conditions "The most vulnerable parts of the course,—will be those sections dealing with topographical mineralogy and the economic aspects."

Most courses in mineralogy should make more use of homework. This in no way increases the contact hours but has a most salutary effect on the student. Problems should be assigned over which the student must puzzle to find the answers. People may forget facts, but they never forget hard work. Homework problems can be given in many things, particularly in the crystallographic portions of the course.

Throughout the course we must not lose sight of the fact that mineralogy is a natural science. Its increasingly close relationship to physics and chemistry may tend to obscure the fundamental difference in the underlying philosophy of mineralogy from that of physical sciences. The mineralogist starts with a crystal as an accomplished fact and from this imperfect reality works toward generalizations regarding structure and properties. The physicist and chemist do the reverse. They work from an idealized picture of perfect structure toward assumed properties, rarely borne out by experience or experiment. A further difference arises from the great concern of the mineralogist for the genetic, historical, and economic consequences of his findings, as well as from his different approach to sources of information. The court of final appeal in mineralogy is the earth's rocky crust itself, rather than the controlled laboratory experiment. This difference is a wholesome one and has much to offer the student in a philosophical sense. Many a student awed by the profound mathematical generalizations and complex technology of physics and chemistry, finds meaning and understanding in physical and chemical principles, in a well-taught course in mineralogy. As teachers of such a course, in our concern with atoms, chemical bonds, and space lattices, we must not become insensitive to the imaginative appeal of the world of minerals that lies in ordered beauty beneath our feet.

Acknowledgments

During the meetings of the Teaching Commission of the International Mineralogical Association in 1962, Dr. Henry E. Wenden was present. He there became aware of the problems of the Commission as well as the nonuniformity of the elementary mineralogy course in the United States. I, consequently, called on him for advice both in formulating the questionnaire and in the preparation of this manuscript. His aid is gratefully acknowledged. I also wish to acknowledge consultation with Dr. Arthur Montgomery on the form and presentation of the questionnaire.

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