DOCUMENT RESUME

ED 224 699 SE 039 739

AUTHOR	Berry, R. W.
TITLE	Crystallization of Magma. CEGS Programs Publication Number 14.
INSTITUTION	Council on Education in the Geological Sciences, Washington, D. C.
SPONS AGENCY	National Science Foundation, Washington, D.C.
REPORT NO	ISBN-0-07-012322-5
PUB DATE	73
NOTE	32p.
PUB TYPE	Guides - Classroom Use - Materials (For Learner) (051)
EDRS PRICE	MF01/PC02 Plus Postage.
DESCRIPTORS	*Classification; *College Science; *Crystallography; Environmental Influences; *Geology; Higher Education; *Kinetics; Science Education; *Science Experiments; Temperature
IDENTIFIERS	National Science Foundation; *Rocks

ABSTRACT

Crystallization of Magma is one of a series of single-topic problem modules intended for use in undergraduate geology and earth science courses. Through problems and observations based on two sets of experiments, this module leads to an understanding of how an igneous rock can form from molten material. Environmental factors responsible for important variations observed in magnetic rocks are stressed. Two fundamental factors affecting or controlling the mineral composition and texture of the resulting rock (initial magma composition and cooling rate) are also stressed. In addition, reasons why scientists classify materials in general and how they classify rocks in particular are explored. However, the ability to name or identify rocks is not a necessary result of attaining the module's goals. Supplemental questions included at the end of the module may prove difficult for the average non-major; they are intended to challenge the superior student. Like other modules in the series, this module is inquiry- and problem-oriented, dealing with interdisciplinary, contemporary, and pragmatic aspects of the subject matter. It is designed to be open-ended so that ideas can be incorporated into higher level classwork. (Author/JN)

CEGS PROGRAMS PUBLICATION NUMBER 14

Crystallization of Magma

COUNCIL ON EDUCATION IN THE GEOLOGICAL SCIENCES
an NSF-funded project of the
AMERICAN GEOLOGICAL INSTITUTE
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CEGS PROGRAMS PUBLICATION NO. 14

Crystallization of Magma

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Edited By
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Council on Education in the Geological Sciences
an NSF-funded project of the American Geological Institute

McGRAW HILL BOOK COMPANY
New York San Francisco St. Louis Montreal Toronto

CONCEPTS IN INTRODUCTORY GEOLOGY: Crystallization of Magma

Library of Congress Catalog Card Number 73-7158

This book was set in Press Roman by Bonnie Harrington, Publications Services. The editors were Brete Harrison and Judith Chaffin, and the production supervisor was Michael A. Ungersma.

The printer and binder was Whitlock Press.

07-012322-5

1234567890 WHWH 79876543

CONTENTS

R. W Berry demonstrates adding replacement acenaphthene crystals to slide in Experiment 2.

FOREWORD

This publication is one of a series of single-topic problem modules intended for use in undergraduate geology and earth science courses. It was prepared under the direction of the Instructional Materials Program (IMP) panel of the Council on Education in the Geological Sciences (CEGS)—a project of the American Geological Institute supported by the National Science Foundation—and is presented through the cooperation of the McGraw-Hill Book Company.

The purpose of modules in this series is to serve as models from which modern aspects of concepts basic to geology can be introduced. Typically, they are inquiry- and problem-oriented and deal with interdisciplinary, contemporary, and pragmatic aspects of subject matter that is difficult to treat in a more ordinary way. Modules are designed to be open ended so that ideas from them can be incorporated into higher level classwork. They should inspire teachers to develop like materials in areas of their own interest and competence.

It is intended that all modules be capable of being used alone, either as fully integrated text/manual/laboratory materials or as a supplementary resource to other course materials. Therefore, they are designed to be self-contained, and their written parts are arranged in a manner that can be adapted to special local needs or conditions. Some are essentially a single laboratory exercise, others might occupy nearly an entire semester to complete satisfactorily. Their breadth is as variable as their depth

In this particular module, the supplemental questions at the end of the text may prove difficult for the average nonmajor. they are intended to challenge the superior student For all who find the module acceptable in its present form, the apparatus, including replacement parts, and text materials (with integrated instructions) are available from the publisher.

The idea for preparation of a module series was presented initially by J. W. Harbaugh, and work on *Crystallization of Magma* was started while he was Director of CEGS. Several versions of this module benefited from the critical testing and evaluation of numerous students and teachers, all of whose efforts we recognize with deep appreciation and gratitude, their suggestions and comments have contributed significantly to the evolution of the module. Early in the evolutionary process, M. N Christensen assumed the difficult task of editor for this publication. In April 1968, J. C Brice of Washington University critically read the initial version, and students under the guidance of G. E. Brogan of San Diego State College conducted the first test. Subsequent tests of equipment and text were performed by students under the direction of J. A Minch, Rio Hondo Junior College (May 1968), O. T. Hayward, Baylor University (September 1968 and June 1969), Murray Felsher, Syracuse University (January 1969); M. L. Crawford, Bryn Mawr College (October 1969), J. L. Weitz, Colorado State University (April 1970), R. N Passero, Western Michigan University (May 1970), Peter Fenner, Governors State University (October 1971); and J V. O'Connor. University of Maryland (May 1972) To all these professors and especially to their perceptive students, we tender our profound thanks.

Throughout the evolutionary process, R. W. Berry, the author, responded with patience and cooperation to the multiple critical inputs.

The color photomicrographs of Hawaiian lava were made available through the courtesy of the U S. Geological Survey

Finally, much credit belongs with R. J. Sederstrom, of Hickok Teaching Systems, and J DeRoy, formerly of that organization, for their work in developing for commercial distribution the experimental apparatus from the author's prototype models, with D. K. Kelty, M. M. Lerette, D. J McKenzie, and J F Paritzky, of the CEGS support staff, who bore the major brunt of the many retypings, and with J E Lewis and F D. Holland, Jr , who were given charge of the end-stage editing phases to which the text was subjected.

Peter Fenner
George R. Rapp, Jr

PREFACE

Through problems and observations based on two sets of experiments, this module should lead you to an understanding of how an igneous rock can form from molten rock material. The approach I have taken stresses the environmental factors responsible for the important variations observed in magmatic rocks I have tried to develop an appreciation for initial magma composition and cooling rate, the two fundamental factors that affect or control the mineral composition and texture of the resulting rock Furthermore, by arranging magmatic rocks according to these properties, similarities and dissimilarities in their origins should become apparent. A secondary goal is to develop an appreciation of why scientists classify things in general, and how they classify magmatic rocks in particular. The ability to name or identify rocks is not a necessary result of attaining either the primary or secondary goals of this investigation. It is sufficiently flexible that as many or as few specific rock names and descriptions may be introduced as is appropriate to meet your needs or to satisfy course requirements.

It may be enlightening to discover that physical and chemical concepts are universally important and are not reserved for formal courses in physics and chemistry You may find the approach of this study frustrating, for you will be asked questions that you cannot readily answer. Do not be discouraged when you're faced with seemingly unanswerable questions, scientists are faced with such questions every day It is exciting to free your imagination and speculate on what a reasonable answer might be.

R W. Berry

EQUIPMENT AND MATERIALS

REQUIRED (supplied with the equipment package):

- Light box with rotating stage and hinged polaroid sheet
- Small polaroid sheet
- Hand lens
- Rock specimens and thin sections of gabbro and basalt
- Single-cavity glass slide A containing crystalline thymol
- Chemical coolant
- Seven-cavity glass slide B containing different proportions of crystalline p-nitrophenol and acenaphthene
- Numbered and lettered vials containing replacement organic chemicals
- Forceps
- Seven 35mm photomicrographic color slides of Hawaiian lava

ACCESSORIES (not supplied):

- Hot plate capable of heating to 130°C
- Stopwatch, or clock or wristwatch with sweep second hand
- Binocular microscope
- Weight scale measuring in grams

OPERATING PROCEDURES:

The *light box* (Fig. 1) serves as a low-power, simplified petrographic microscope equipped with a low-temperature-heating (and viewing) stage. Its light and heat source is a 150-watt bulb, and its optical system is a hand lens. The cavity-bearing slides and rock thin sections should be viewed by inserting them into the

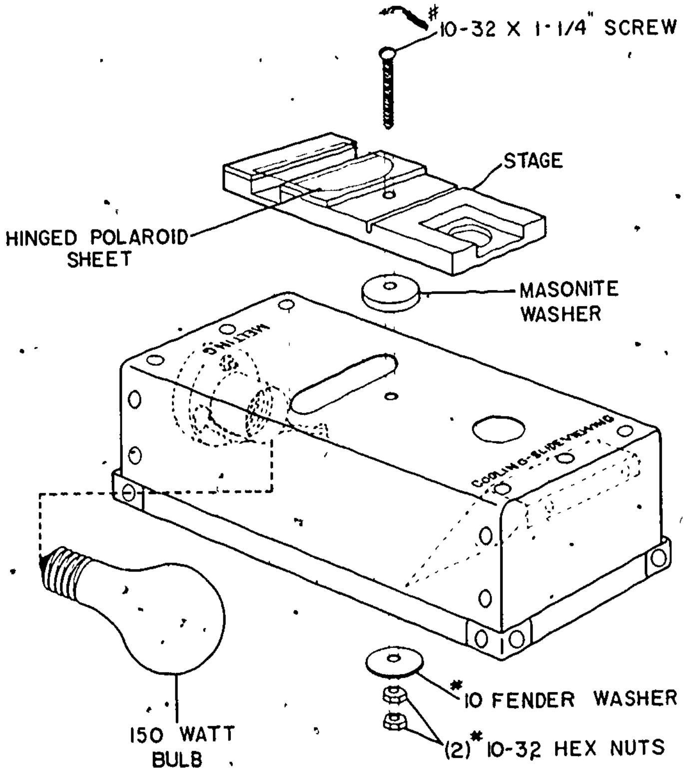

Fig. 1 Exploded view of light box with rotating stage and hinged polaroid sheet.

slot on the stage beneath the hinged polaroid sheet, to facilitate handling the slides and thin sections, this sheet should be folded back, away from the slot. When melting the organic compounds in the cavity slides, always orient the slide with the cavity or cavities facing upward and rotate the stage until the slot is positioned directly above the oblong opening of the box over the light bulb (in the position labeled "melting"). **Warning! Avoid contact between these compounds and your skin. Melting these compounds should be undertaken in a well-ventilated room, breathing the vapors for prolonged periods may produce headaches and other irritations.** When the stage is rotated 180° to the cooling slide viewing position (with the slot directly above the circular opening over the mirror), the slide will cool sufficiently for crystallization to take place With the hinged polaroid sheet lying flat over the slot and the *small polaroid sheet* inserted beneath the slide or thin section, the number of directions in which the light vibrates is controlled in a manner approximating the effect of the "crossed nicols" of a sophisticated petrographic microscope. Materials through which light is transmitted equally in all directions are called "isotropic" and will appear dark, those through which light is not transmitted uniformly in all directions are called "anisotropic" and will appear varicolored The contrast between the melted (dark) and crystalline (colored) organic materials used in your experiments is dramatic and improves the ease of observing melting and crystallization processes. Good explanations of the behavior of materials in polarized light occur in Ernest E. Wahlstrom's *Optical Crystallography* (4th edition, John Wiley & Sons, 1969) and F. D. Bloss' *Introduction to the Methods of Optical Crystallography* (Holt, Rinehart & Winston, 1961). **Warning! Polarizing properties of polaroid are lost when the sheets are exposed to excessive heat. Unless specifically directed to do otherwise, do not insert small polaroid sheet beneath a cavity slide while it is in heating (melting) position.** The *photomicrographic color slides of Hawaiian rocks*, used to study crystallization of basaltic lava, may be viewed by placing them in the square recess at the end of the stage away from the slot and orienting the square recess of the stage in the cooling position.

For best results, hold the *hand lens* as close to your eye as comfortable, then, in good light bring the sample you wish to observe toward the lens until it is in sharp focus (usually a distance of 2 to 8 centimeters) Observing crystallization of the organic compounds through a binocular microscope greatly enhances the dramatic effect of the process.

To appreciate rock textures, *rock specimens* and *thin sections* should be studied together. Specimens and thin sections of basalt and gabbro are included in the equipment package, but these should be augmented by examples of as many additional igneous rocks as are appropriate for your needs or for the requirements of the course.

The *single-cavity glass slide A* contains the crystalline organic compound thymol ($[CH_3]_2CHC_6H_3[CH_3]OH$) ready for use. Additional thymol crystals in the vial labeled "T" are for replacing any of the compound that might escape from the slide and for seeding the molten thymol during the cooling phase of Experiment 1. Should it become necessary to replace or augment the thymol in the cavity, place the slide in the melting position on the light box and add fresh crystals to the cavity. When the cavity is about half filled with melted thymol, rotate the stage to the cooling position and allow the melt to crystallize. Because of thymol's tendency to solidify slowly without crystal formation, you will probably have to seed it with a tiny fragment of solid thymol. If the fragment melts instead of growing, wait a minute and seed again. Thymol expands as it crystallizes, so be certain that the cavity is only half filled before crystallization begins. **Warning! Any experiment that involves thymol should be done under a hood or in a well-ventilated room. Avoid breathing the thymol vapors directly from the molten material. Avoid contact between thymol and your skin.**

Experiment 1 requires a means for cooling slide A quickly. The *chemical coolant* in the spray can supplied in the equipment package may be used if the spray is directed only at the under side of the slide. Block, cube, or crushed ice are equally effective, but may damage the glass slide. Cold packs such as those used in portable ice chests are also effective and eliminate the problem of coping with meltwater.

The *seven-cavity glass slide B* contains various pure and mixed samples of the organic compounds p-nitrophenol ($NO_2C_6H_4OH$) and acenaphthene ($C_{10}H_6[CH_2]_2$). These will be used to examine the crystallization of mixtures in Experiment 2. The number scribed near each cavity identifies the compound in that cavity and in the vial bearing the same number, the proportions of the compounds, expressed in weight percent, are listed in Table 1 immediately preceding the instructions for Experiment 2. The crystals in the cavities will melt when the slide is placed on the light box directly over the light/heat source, however, the experiment will proceed more smoothly and quickly if the slide is placed on a *hot plate* (preheated to 130°C) until all crystals in all cavities are melted. Melting should require no longer than 2 or 3 minutes and should be monitored constantly to avoid burning the compounds. Once the crystals are melted, the slide should be placed (using the forceps) in the slot on the stage and the stage rotated to the cooling position. The mixtures of p-nitrophenol and acenaphthene crystals in the numbered vials are supplied to replace, as needed, any of the materials in the slide (see frontispiece). A total weight of 0.06 grams of mixture of the two materials is suitable to match the percentages listed in Table 1. (The weight scale, reading in grams, may be used to prepare additional mixtures should the supply in the vials be exhausted.) The mixtures in the cavities will turn brown after several heating cycles. The change in color will be more rapid if the slide is heated to temperatures greatly in excess of 130°C or if it is heated to 130°C for excessive periods of time. The discoloration should not affect the results of the experiment unless the coloring becomes so deep that it interferes with the viewing of the crystallization process. Warning! Any experiment that involves melting p-nitrophenol or acenaphthene should be done under a hood or in a well-ventilated room. Avoid breathing vapors directly from the molten material.

A *stopwatch* or a *clock or wristwatch* with a sweep second hand is needed for timing the formation of crystals in Experiment 2.

Forceps are necessary for handling the heated glass slides A and B.

INTRODUCTION

Melted rock material, called lava, has been erupted from many volcanoes and has been observed to cool and solidify to form hard rocks. Geologic evidence indicates that some rocks now exposed at the earth's surface were originally formed by solidification, or crystallization, of magma (the unerupted equivalent of lava) deep within the earth. The purpose of this module is to study the phenomena of melting and freezing in order to understand better the processes that produce the textural and mineralogic varieties of volcanic (erupted) and plutonic (unerupted) igneous rocks. The terms "freezing," "solidification," and "crystallization" are essentially synonymous for purposes of this investigation. The term "crystallization" is preferred in this context, because it indicates most precisely the process with which we are concerned.

Before proceeding further, you should be able to identify some common rock-forming minerals, including quartz, orthoclase feldspar, microcline feldspar, plagioclase feldspar, olivine, biotite, muscovite, amphibole, pyroxene, ilmenite, and apatite. Some terms you need to know and understand include the following.

Andesite: fine-grained, volcanic igneous rock composed largely of sodic (Na-rich) plagioclase (andesine), biotite, pyroxene, and the amphibole, hornblende.

Aphanitic: igneous-rock texture: crystalline constituents too small to be distinguished without magnification.

Basalt: fine-grained, dark-colored, usually volcanic, basic (silica-deficient) igneous rock composed largely of calcic (Ca-rich) plagioclase and ferromagnesians.

Bathylith (=Batholith): large body of plutonic igneous rock whose diameter or breadth remains constant or increases with depth.

Diorite: coarse-grained, plutonic equivalent of andesite.

Gabbro: medium- to coarse-grained, plutonic equivalent of basalt.

Granite: coarse-grained, usually light-colored, plutonic, acid (silica-rich) igneous rock composed largely of quartz, potassic (K-rich) feldspars (orthoclase, microcline), and micas.

Magma: naturally occurring mobile rock material formed within the earth.

Phaneritic: igneous-rock texture: essential crystalline constituents distinguishable without magnification.

Phenocryst: comparatively large crystal in porphyritic igneous rock.

Porphyritic: igneous-rock texture: larger crystals set in finer crystalline or glassy groundmass or both.

Plutonic: class of igneous rock formed beneath the earth's surface (=intrusive), often at great depth and under high pressure.

Rhyolite: fine-grained, volcanic equivalent of granite.

Syenite: coarse-grained, plutonic igneous rock composed primarily of potassic (K-rich) feldspars, biotite, pyroxene, or amphibole (especially hornblende), and sometimes nepheline.

Trachyte: fine-grained, volcanic equivalent of syenite.

Volcanic: class of igneous rock formed at or above the earth's surface (=extrusive).

In this module, you will describe and compare two common varieties of igneous rock. Then, you will observe processes of freezing and melting in the laboratory. Next, you will observe a set of thin sections made of samples taken from one Hawaiian lava flow during the time it was crystallizing. Finally, you should observe a variety of naturally occurring igneous rocks, the number depending on your individual needs or the course requirements. At the outset, however, some principles of kinetic theory are introduced by which some aspects of the phenomena of freezing and melting can be explained.

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PRELIMINARY EXERCISES

The preliminary exercises will be most beneficial if done before laboratory time. If this is impossible, complete the exercises after the laboratory work is finished and reevaluate your laboratory work in the light of the concepts presented here.

KINETIC THEORY OF HEAT AS AN EXPLANATION OF MELTING

A solid has a definite shape, volume, and density because its atoms are tightly bonded together by electrostatic or other bonding forces. At all temperatures above absolute zero (-273°C), however, atoms in a crystal have kinetic energy (i.e., they vibrate or rotate) as a result of the heat content of the crystal. Indeed, the temperature of any substance is a direct measure of the average kinetic energy of its component atoms or groups of atoms. If heat is added to a crystal at any temperature, atoms in the crystal vibrate more energetically and, in effect, each atom occupies a slightly larger space within the crystal, thus a crystal expands as it is heated. As more heat is added to a solid, the average kinetic energy of its atoms eventually becomes sufficient to overcome the forces that bond the atoms together, allowing atoms to separate and be free to move with respect to each other. The strength of bonds holding atoms together depends upon the kinds of atoms of which the crystal is composed.

When its atoms separate due to heating, a crystal melts. The melting point, which is equal to the freezing point, is the temperature at which the average kinetic energy of an atom of a crystal is just equal to the energy that bonds atoms together. In liquids, the kinetic energy exceeds the bonding energy, in solids, the bonding energy exceeds the kinetic energy.

Why do you think different solids have different melting temperatures?

Nothing was mentioned about the effects of pressure. Do you think that increasing the pressure on a solid would raise its melting temperature? lower its temperature? leave it unaffected? Why?

KINETIC THEORY OF HEAT AS AN EXPLANATION OF FREEZING

Freezing occurs when bonding forces that attempt to pull atoms and molecules tightly together are strong enough to overcome the energy of motion (kinetic energy) which tends to keep atoms and molecules separated. Above the melting temperature, energy of motion dominates and atoms are free to move relative to each other. The laws of chance indicate that moving atoms will collide and will be momentarily bonded together. Groups of atoms bonded together at temperatures in excess of the melting point will not stay bonded together very long because kinetic energy will quickly separate them again. As the temperature is lowered to the freezing point, groups of atoms brought together by random movements will be bonded with sufficient strength to overcome their own kinetic energy and thus be held together. However, the small centers of solidification (nuclei of crystals) must withstand more than the kinetic energy of their own atoms. Other atoms surrounding the centers are also vibrating and will tend to collide with and disassociate the nuclei as quickly as they form. As the temperature of the melt approaches the freezing point, a few nuclei will survive the bombardment by surrounding atoms, but most nuclei will still be broken up and their atoms released to find other nuclei to bond with. As the temperature is lowered below the freezing point, kinetic energy decreases. As a result, more groups of atoms remain unbroken by the disruptive forces of vibration, and some groups begin to grow by bonding additional atoms to themselves. As the temperature drops well below the freezing point, most of the groups that form can withstand all attempts to break them apart, so there will be many nuclei growing simultaneously. If the atoms in the groups are bonded together in a regular orderly arrangement, the group is called a crystal and the process of freezing is called crystallization. If the atoms in the groups are randomly arranged relative to each other, the resultant solid is noncrystalline or glass.

If a given volume of molten material is cooled slowly, would you expect a greater or lesser number of crystals to form than if the volume were cooled rapidly? Why?

Would you expect crystalline solids that formed by quick cooling to be made of larger or smaller crystals than crystalline solids which formed by slow cooling? Why?

It has been noted that crystalline materials of differing compositions will be made up of crystals of different sizes even though all materials were cooled at the same rate. How can you account for this?

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EXPERIMENTAL EXERCISES

VOLCANIC AND PLUTONIC ROCK TEXTURES

Basalt and gabbro are different rocks with similar chemical and mineralogic compositions but with different textures. (A rock texture is a description of the size, shape, and arrangement of the rock's constituent crystals.) Basalt has been observed to form by the cooling and crystallization of certain kinds of lava. Geologic field evidence, on which your instructor may wish to elaborate, indicates that gabbros form by crystallization of magma far below the earth's surface. Study and compare the rock specimens and the thin sections of these rocks supplied in the equipment package.

Thin-Section and Rock Observations

EQUIPMENT:

Light source
Rock specimens and thin sections of gabbro and basalt
Hand lens
Small polaroid sheet

PROCEDURE:

Place each thin section, in turn, in the slot of the stage and rotate the stage to the cooling-slide-viewing position. View the thin sections through the hand lens, both with and without the polaroid sheets in place (Fig. 2). Examine the rock specimens through the hand lens under strong, preferably natural, light.

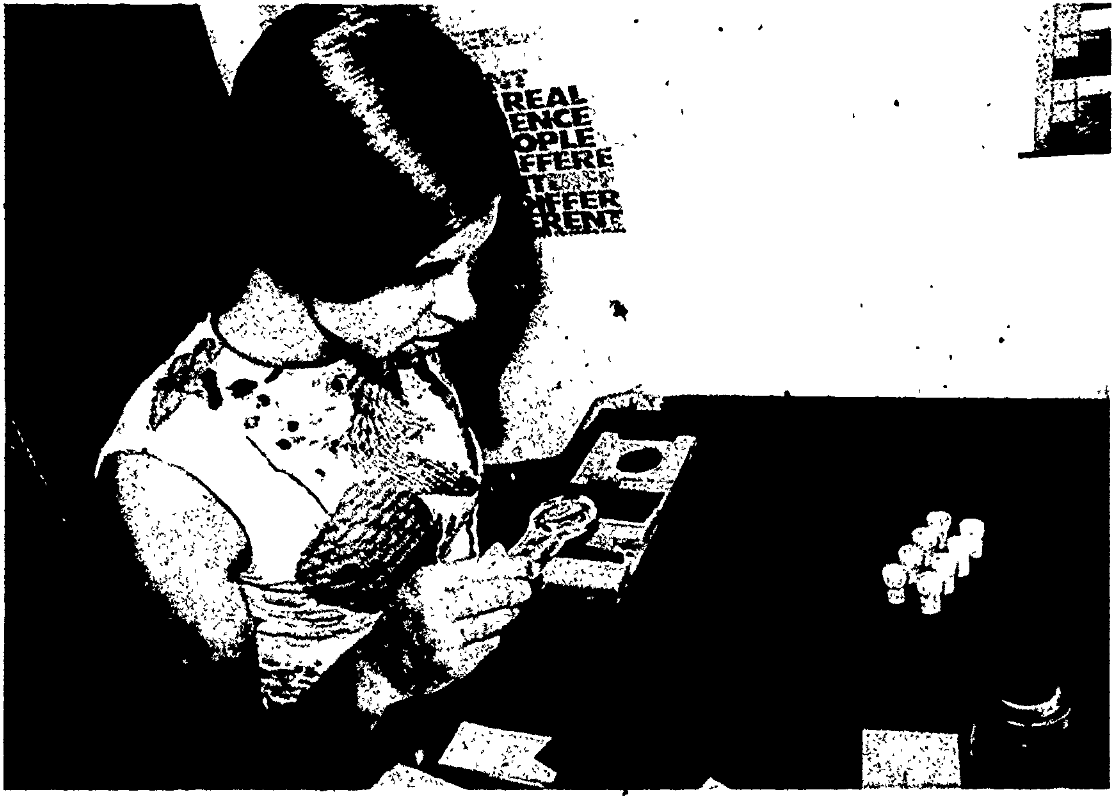
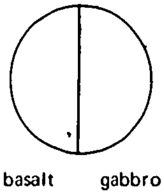


Fig. 2 Observing texture in thin section of basalt. Thin section in slot of stage; stage rotated to cooling-slide-viewing position; polaroid sheets not in place, permitting view of thin section under direct illumination. (Photo by C. L. Carter)

Describe the differences between basalt and gabbro that you observe in rock specimen and thin section. If necessary, ask your instructor to help you identify the minerals seen in the thin sections. Sketch the textures you see in the thin sections.



How can you explain the differences you observe on the basis of the field occurrence of each kind of rock and what you know at the present about processes of crystallization?

OBSERVATION OF FREEZING AND MELTING

Formation of igneous rocks by crystallization of lava is difficult to observe in the laboratory because melting temperatures are so high (600°C to 1200°C) that special equipment and precautions are necessary to handle the melts. In order to understand better the processes of melting and freezing, you will experiment with organic solids that have melting temperatures close to 100°C. These organic solids are used as models of natural rocks.

Because of simplification, a model's portrayal of natural phenomena is usually limited. Whenever you deal with a model, therefore, you should attempt to determine its limitations and to evaluate the conclusions you draw from the model in the light of those limitations. Some of the ways in which the simplified laboratory models used in this module differ from their silicate-melt counterparts in nature include the following.

1. The temperature of crystallization in the model is near room temperature; silicate melts crystallize at temperatures between 600°C and 1200°C.
2. The model is composed of organic solids rather than inorganic silicate minerals.
3. The pressure of crystallization of the model is one atmosphere; magmas crystallize through a large range of pressures.
4. The time of crystallization in the model is a few minutes; lava flows crystallize in weeks, months, or years, and crystallization of plutonic rocks may take centuries, millennia, or even longer.
5. The volume of the model is a few cubic centimeters. Some bodies of igneous rock have volumes of thousands of cubic kilometers.

Experiment 1

Warning! **Do not perform this experiment in a poorly ventilated room. Avoid direct inhalation of the vapors. A small portable fan may be useful for disbursing vapors, but do not place it too near the heat source.**

EQUIPMENT:

Source of light and heat
Single-cavity slide A containing thymol crystals
Hand lens
Small polaroid sheet
Suitable means for quickly cooling slide A
Forceps
Hot plate (optional)

PROCEDURE:

Place slide A in the slot of the stage and rotate the stage to the melting position. From time to time, insert very carefully with the forceps the smaller polaroid sheet beneath the slide (Fig. 3), swing the hinged polaroid sheet over the slide, and through the hand lens observe the crystals as they melt. Do not leave the polaroid sheets in place for very long at a time because of the danger of damaging the sheets or destroying their polarizing qualities. **Always use forceps to handle hot glass slides.**

Fig. 3 Inserting small polaroid sheet beneath forceps-held single-cavity slide while observing melting of thymol crystals. *See cautionary notes in text.* Stage rotated to melting position. (Photo by C. L. Carter)

What parts of crystals begin to melt first?

How can you explain why all the crystals do not melt simultaneously, i.e., why, as melting proceeds, do some crystals melt first, leaving isolated solid crystals?

After the thymol has melted, revolve the stage so that slide A is in the cooling position. Through the hand lens and both with and without the polaroid sheets in place, observe the formation of new crystals during the process of crystallization. To hasten the onset of crystallization, add a small crystal of thymol to the liquid thymol. If this "seed" crystal melts, wait a minute and seed again.

Describe the process of crystallization as you observe it. Include a sketch of the texture of the mass of crystals after crystallization is completed.

Remelt the thymol and allow it to cool as you did previously.

What is the difference in the rate of cooling? in the size of the crystals, relative to the size of the crystals produced after the first melting?

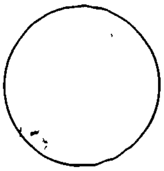
Again, remelt the thymol. Quickly cool the slide, preferably using the chemical coolant (Fig. 4). Be careful not to spill the thymol or allow any meltwater (if you are using ice) to get into the slide. If crystallization does not begin right away, seed the slide as described above.

Describe the process of crystallization and sketch the texture of the mass of crystals.

Again, remelt the thymol and allow it to cool slowly until a few crystals are growing. Then cool it quickly, using the chemical coolant.

Fig. 4 Cooling forceps-held single-cavity slide rapidly with chemical coolant. Stage in melting position; polaroid sheets not in place for viewing. (Photo by C. L. Carter)

Describe and sketch the texture of the mass of crystals. What is the term for this texture?



What effect does the rate of cooling have on the texture of crystalline thymol? How do these observations compare with your inferences from theory in the preliminary exercises?

Compare the textures you have seen in thymol with the textures of basalt and gabbro. Is the comparison consistent with what is known about the natural occurrence of these rocks? Explain.

Note that crystalline thymol is homogeneous, it consists of crystals of only one kind. Basalt and gabbro are mixtures of several kinds of crystals. The next part of the module deals with crystallization of heterogeneous substances, or mixtures of different materials.

CRYSTALLIZATION OF MIXTURES

In this experiment you will use a slide containing mixtures of two organic substances (p-nitrophenol and acenaphthene) in various proportions. You will melt these mixtures and then observe their recrystallization. First examine the characteristics of crystals of acenaphthene (cavity 1) and of p-nitrophenol (cavity 7) so that you can distinguish the two substances in the mixtures. The numbers of the cavities are scribed on the top surface of the slide.

Describe and sketch the crystalline characteristics of acenaphthene and p-nitrophenol.

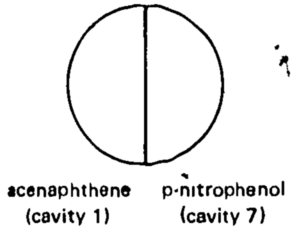


TABLE 1 Composition of material in cavities on slide B

Cavity number	*Acenaphthene, weight percent*	*P-nitrophenol, weight percent*
1	100	0
2	80	20
3	67	33
4	50	50
5	33	67
6	20	80
7	0	100

After melting all the mixtures, we will be concerned with the *temperature* at which the first crystals appear in the various mixtures and with the *kind of crystal* that forms first. In order to measure temperature precisely, we would need more elaborate equipment than is available. However, we can achieve a qualitative measure of *relative* temperature by simply measuring elapsed time. Once all the material in all the cavities is melted, the time until crystallization begins, following removal of the slide from the hot plate, becomes a measure of relative temperature. The longer the cooling time, the lower the temperature of the material. (For those of you who have had chemistry, it might be interesting to consider the effects, assuming the reaction to be on the one hand essentially exothermic, on the other essentially endothermic.)

Experiment 2

Warning! Do not perform this experiment in a poorly ventilated room. Avoid direct inhalation of the vapors.

EQUIPMENT:

Light and heat source
Seven-cavity slide B containing mixtures of p-nitrophenol and acenaphthene in varying proportions
Hand lens
Small polaroid sheet
Forceps
Stopwatch or wristwatch with sweep second hand
Hot plate (optional)

PROCEDURE:

Place slide B on a hot plate, preheated to 130°C, until the crystals in all cavities have melted completely. If a hot plate is not available, swing the stage of the light and heat source so that it does not obstruct the oblong opening on the top of the box and carefully balance the slide directly on the box over the heat source (Fig. 5). Once all the crystals have melted, with forceps transfer the slide to the stage rotated to the cooling position and observe the crystals as they form.

Fig. 5 Moving forceps-held seven-cavity slide from top of box to slot on stage preparatory to viewing crystallization of pure and mixed compounds, following melting of compounds with slide placed directly over light/heat source. *See cautionary notes in text.* Stage rotated to position intermediate between melting and cooling-slide-viewing positions to permit placing slide directly on box. (Photo by C. L. Carter)

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Note the number of the cavity in which you first see a crystal begin to form and start the stopwatch when you first see the crystal. Record a "0" in the first column of the data sheet (below) opposite the appropriate cavity number, also note the *kind of crystal* that first appears. Note the number of the next cavity in which you see a crystal beginning to form. Record the time (in seconds) that has elapsed since crystallization began in the first cavity, and record the kind of crystal forming now (Fig. 6). Proceed to record elapsed time and kinds of crystals until crystallization has begun in all cavities and the data sheet below is completed. You may have to reheat and cool the mixtures to complete the table, if so, double check your recorded data where possible. Your instructor may wish to conserve time by helping you complete your table if time is running short. However, many things in science are time-consuming, and you may find that progressing slowly, one cavity at a time, will prove in the long run to be the fastest and most rewarding approach

Experiment 2 Data Sheet

Cavity number	*Elapsed time (seconds)*	*Kind of crystal that forms first (acenaphthene or p-nitrophenol)*
1		
2		
3		
4		
5		
6		
7		

What are the proportions of acenaphthene and p-nitrophenol that remain completely melted for the longest time, that is, to the lowest temperature?

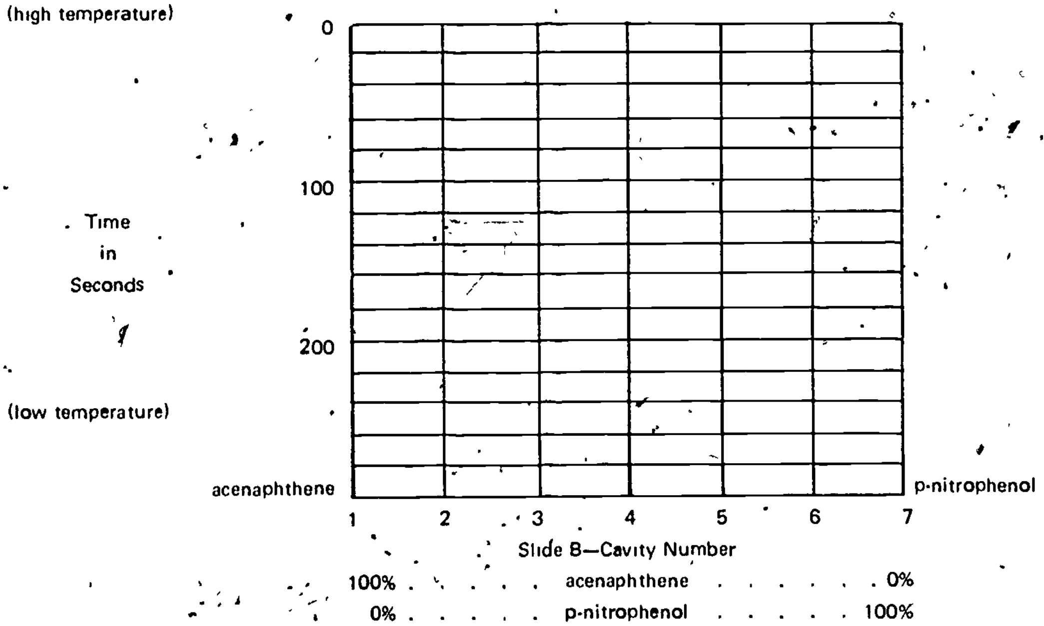
Fig. 6 Observing and timing crystallization of pure and mixed compounds on seven-cavity slide. *See cautionary notes in text.* Slide in slot of stage; stage rotated to cooling-slide-viewing position; hinged polaroid sheet in place for viewing; small polaroid sheet not in use. (Photo by C. L. Carter)

Does the admixture of a second substance raise or lower the crystallization (and melting) temperature of a pure substance? (What you have observed here is a general property of mixtures.)

Can you suggest any reasons why the freezing temperatures of substances in mixtures are different from those of the pure substances? If so, explain.

Plot your data (time of initiation of crystallization versus composition of mixture) from the experiment on the following graph and draw lines to connect the points.

Experiment 2 Phase Diagram



Remember that in this particular experimental model, increasing time represents decreasing temperature, so the time scale represents higher temperatures at the top and lower temperatures at the bottom. The observation of changes in *temperatures* of initiation of crystallization with changes in composition of the melt is the goal of this model experiment. In nature, temperatures might increase, decrease, or remain unchanged through a given period of time.

For the mixtures listed below, predict the temperature (in terms of time at the particular state of cooling you happened to see) at which crystallization begins and the composition of the first crystal to form.

Mixture	*Time*	*Composition of first crystal*
75% acenaphthene 25% p-nitrophenol		
60% acenaphthene 40% p-nitrophenol		
40% acenaphthene 60% p-nitrophenol		
25% acenaphthene 75% p-nitrophenol		

In liquids from which acenaphthene is the first crystal to form, how must the composition of the residual liquid change as crystals grow in it? In liquids from which p-nitrophenol is the first crystal to form, what must happen to the composition of the residual liquid as crystals grow in it?

What effect does the original composition of a melt have on the kinds and relative amounts of crystals that form from it?

Assume you could draw off some of the liquid from a cavity (other than 1 or 7) after crystallization had begun but before it was complete. Assume further that you could place the liquid in an empty cavity and observe it as it crystallized. Compare what you believe would be the similarities and differences between what you would see in the new cavity after crystallization was complete and what you would have seen after crystallization was complete in the original cavity had you not separated the liquid.

Fig. 7 Observing color photomicrograph of Hawaiian lava. Transparency in slide-accommodating square recess of stage; stage rotated to cooling-slide-viewing position. (Photo by C. L. Carter)

CRYSTALLIZATION OF BASALTIC LAVA

Having observed the process of crystallization through experiments, we will now consider the effects of progressive crystallization of a basaltic lava. With the slide-accommodating square recess of the stage oriented in the cooling position of the light box, place the seven 35mm transparencies, in turn and in order, in the recess for viewing (Fig. 7). These slides are photomicrographs of samples of Hawaiian basaltic lava collected from Makaopuhi lava lake following its formation in association with the eruption of Kilauea in March 1965. The samples were taken at various temperatures and thus at various degrees of crystallization. As soon as it was collected, each sample was chilled rapidly to change the molten portion of the lava to glass before additional crystals could form. The crystals that you see were in existence in the molten lava before it was sampled.

An eruption of the volcano that produced the lava you will study is shown in a spectacular film entitled "Eruption of Kilauea, 1959–60."[4] The film can be obtained from the U.S. Department of Agriculture, Office of Information, Washington, D.C. 20250, or from the U.S. Geological Survey, Visual Services, Washington, D.C. 20242. If you have not already seen it, it is highly recommended not only for its striking visual impact but also for its sequences showing how data were collected at the site of the eruption.

Presented in Table 2 are data taken from the U.S. Geological Survey information sheets that accompanied the original thin sections—keyed by number to the photomicrographic slides.

TABLE 2 Summarized information on Hawaiian lava photomicrographs

Slide number	*Estimated temperature of collection (in °C)*	*Glass content (%) and color (representing molten lava at collection time)*	*Minerals visible*
1	1170	90% Light yellow brown	Large olivine crystals, small pyroxene and plagioclase crystals.
2	1130	76% Darker brown than slide 1,	Same as slide 1 but with increased abundance of plagioclase and pyroxene.
3	1075	44% Dark reddish brown	Olivine present in rock but not shown in this slide. Note the increase in pyroxene and plagioclase from slide 2.
4	1065	42% Similar to slide 3	Same as slide 3 but with a few opaque crystals of ilmenite.
5	1020	8% Very light brown	Olivine present in rock but not shown in this slide. Pyroxene and plagioclase have increased greatly in abundance from slides 3 and 4. Opaque minerals have increased greatly in abundance from slide 4. Note needles of apatite in the glass.
6	865–920	6% Nearly colorless	Olivine crystals still large and surrounded by pyroxene, plagioclase, and opaque minerals. Glass not visible in slide but reported by USGS observers.
7	725–795	4% Color not reported	Same as slide 6, but showing alteration of the olivine (reddening).

With respect to decreasing temperature, in what order did the minerals in the basalt crystallize?

Describe the difference between the appearance of the olivine in slide 1 and the olivine in slide 6. Account for the difference.

Basaltic lava crystallizes at a higher temperature than any other kind of lava. Some rhyolitic lavas may still be partly melted at temperatures as low as 700°C. Most lavas are similar in that they are composed of essentially the same elements. They differ in that they contain these elements in different proportions

Based on your observations in Experiment 2, explain why different lavas may have different melting points.

How might a nonbasaltic igneous rock be formed from a magma of basaltic composition?

IGNEOUS-ROCK CLASSIFICATION

Geologists often use systems of classification that have genetic significance, i.e., the name used in a classification brings to mind both a particular object and a particular mode of origin for that object In the case of igneous rocks, you have now seen that two features (textures and mineral content) tell us something about the origin of the rock.

The number and variety of igneous rock hand specimens you will examine will vary depending on individual needs or course requirements. However, the following should be considered an absolute minimum. granite, rhyolite, gabbro, basalt, and pyroclastics. Hopefully, these will be supplemented by examples of syenite, trachyte, diorite, and andesite. Some if not all rock types should exhibit a variety of textures. Classify the rocks according to texture and mineral content, and indicate where each belongs on the chart below. (Note that this chart is set up only for crystalline textures.)

Mostly light-colored rocks with some quartz	*Mostly light-colored rocks with potassium-feldspar and without quartz*	*Rocks rich in medium-colored amphibole, pyroxene, and plagioclase feldspar*	*Dark-colored rocks rich in pyroxenes and olivine; feldspar if present is plagioclase*

increasing crystal size: fine → coarse

light ⟷ dark

(olivine is considered a dark mineral)

Without worrying too much about the locations of your samples on this classification diagram, what implications can you read from the results of what you have plotted?

SUPPLEMENTAL QUESTIONS

S-1. Where do you think the magma that crystallizes to form gabbro comes from?

S-2. Where do you think that lava that crystallizes to form basalt comes from?

S-3. If, as this module suggests, the compositions of gabbroic magma and basaltic lava are essentially the same, why do gabbro and basalt have different textures?

S-4. Why doesn't all gabbroic magma break through to the surface to become basaltic lava?

S-5. Some basalts are porphyritic. They may contain phenocrysts of olivine or plagioclase feldspar. Explain this texture in the light of what you have learned from experiments with organic solids. Devise an additional experiment to test your hypothesis.

S-6. Geologists differ in opinion concerning the origin of granitic magma. (1) Some say it forms when gabbroic magma partially crystallizes and the residual magma (which may be of granitic composition) is separated in some way from the crystals. (2) Others say that granitic magma results from the total melting of preexisting rocks that, although not granite themselves, are of the same composition as granite, e.g., a sandstone rich in quartz and orthoclase feldspar. (3) Another idea, similar to 2, is that preexisting rocks first begin to melt around the grain boundaries of minerals having relatively low-temperature melting points such as quartz and orthoclase feldspar. If this liquid were in some way separated from the residual unmelted grains, it would be a granitic magma. Evaluate the validity of each of these hypotheses in the light of what you have learned from this module.

S-7. Many geologists feel that some granites were not produced by the crystallization of any kind of magma. Develop a hypothesis to account for a granite without directly involving freezing or melting.

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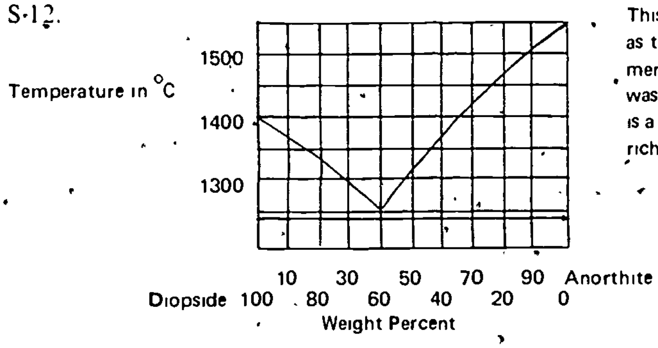
S-8 Some molten materials will cool below their temperatures of crystallization without forming crystals. Thymol in slide A is an example of this, therefore, you may have found it necessary to "seed" the thymol before it started to crystallize. Explain this in terms of what you have learned about the process of freezing.

S-9. Explain why the still molten portions of the Hawaiian lava samples turned to glass rather than crystallizing when the samples were chilled.

S-10 Explain why glass may be considered a supercooled liquid.

S-11. During the crystallization of the organic substances in slide B, you should have noted a change in appearance of the material in all cavities (with the exception of 1 and 7) at about the same time that the first crystal began to form in the material that was the last to crystallize. The change resembled a fog moving through the mass of crystals already formed. After the change, the substance in each of the affected cavities looked somewhat milky. What was happening in the cavities when this change took place?

S-12.



This phase diagram is of the same general type as the one you constructed earlier. The experimental work necessary to construct the diagram was done by a geologist named Bowen. Diopside is a pyroxene mineral and anorthite is a calcium-rich plagioclase feldspar

For the following proportions of anorthite and diopside, (1) give the temperature at which the first crystal forms, (2) give the composition of the first crystal, and (3) describe in each case how the composition of the melt would change as crystallization progressed.

a. 20 percent diopside . 80 percent anorthite
b. 80 percent diopside : 20 percent anorthite
c. 50 percent diopside : 50 percent anorthite

S-13. Do the temperatures of crystallization of diopside and anorthite in varying proportions as determined by Bowen in the laboratory (see diagram for previous question) agree well with the temperatures and proportions of pyroxene and plagioclase in the Hawaiian samples studied in an earlier exercise? Explain in detail why you believe as you do.

CEGS PUBLICATIONS (continued from front cover)

CEGS PROGRAMS PUBLICATION SERIES

1. Problems in Physical Geology, by George R. Rapp, Jr., and others. 1967; *Jour. Geol. Education,* v. 15, no. 6, p. 219-279. Now available only without answers.
2. Bibliography of Statistical Applications in Geology, by James C. Howard. 1968 (reprinted with corrections, 1972), 24 p.
3. * Fund Sources for Undergraduate Geology, edited by Peter Fenner. 1969, 13 p.
4. Audio-Tutorial Instruction: A Strategy for Teaching Introductory College Geology, edited by Peter Fenner and Ted F. Andrews. 1970, 22 p.
5. Requirements in the Field of Geology, edited by Robert G. Reeves and David M. Delo. 1970, 38 p.
6. Teaching Introductory College Geology by Television, by John E. Bowen, and others. 1971, 38 p.
7. Dimensions of a Planet, by O. T. Hayward, L. W. Epps, and R. G. Font. 1971, 45 p.
8. Undergraduate Geology: A Strategy for Design of Curricula, by F. H. T. Rhodes, and others. 1971, 79 p.
9. An Annotated Bibliography of 16mm Films Useful in College-Level Geology and Earth Science Courses, by Noel Potter, Jr., Richard L. Bartels, and George R. Rapp, Jr. 1971, 50 p.
10. Papers on Low-Temperature Geochemistry, edited by Gale K. Billings, and others. 1972, *Jour. Geol. Education,* v. 20, no. 5, p. 217-272.
12. Introductory Geology: Aspects and Options, by John E. Bowen, and others. 1972, 48 p.
14. Crystallization of Magma, by R. W. Berry. 1973, 20 p.

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