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Techniques of Water-Resources Investigations
of the United States Geological Survey

CHAPTER D1

APPLICATION OF SURFACE GEOPHYSICS TO GROUND-WATER INVESTIGATIONS

By A. A. R. Zohdy, G. P. Eaton,
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BOOK 2
COLLECTION OF ENVIRONMENTAL DATA

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PREFACE

The series of manuals on techniques describes procedures for planning and executing specialized work in water-resources investigations. The material is grouped under major subject headings called "Books" and further subdivided into sections and chapters. Section D of Book 2 is on surface geophysical methods.

The unit of publication, the chapter, is limited to a narrow field of subject matter. This format permits flexibility in revision and publication as the need arises. "Application of surface geophysics to ground-water investigations" is the first chapter to be published under Section D of Book 2.

CONTENTS

FIGURES

Metric Units of Measurement

Many of the analyses and compilations in this report were made in metric units of measurements. The equivalent English units are given in the text and illustrations where appropriate. To convert metric units to English units, the following conversion factors should be used:

Metric units	Conversion factor	English units
Length in centimeters (cm) ----	×0.394	=inches
in meters (m) ----	×3.281	=feet
in kilometers (km) ----	×0.6214	=miles
Area in square kilometers (km^2) ----	×0.386	= square miles
Slope in meters per kilometer (m/km) ----	×5.28	=feet per mile

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Abstract

This manual reviews the standard methods of surface geophysics applicable to ground-water investigations. It covers electrical methods, seismic and gravity methods, and magnetic methods.

The general physical principles underlying each method and its capabilities and limitations are described. Possibilities for non-uniqueness of interpretation of geophysical results are noted. Examples of actual use of the methods are given to illustrate applications and interpretation in selected geohydrologic environments.

The objective of the manual is to provide the hydrogeologist with a sufficient understanding of the capabilities, limitations, and relative cost of geophysical methods to make sound decisions as to when use of these methods is desirable. The manual also provides enough information for the hydrogeologist to work with a geophysicist in designing geophysical surveys that differentiate significant hydrogeologic changes.

Introduction

This manual is a brief review of the standard methods of surface geophysical exploration and their application in ground-water investigations. It explains the capabilities of exploration geophysics and, in a general way, the methods of obtaining, processing, and interpreting geophysical data. A minimum of mathematics is employed, and the scope is limited to an elementary discussion of theory, a description of the methods, and examples of their applications. It is in no sense intended as a textbook on applied geophysics. Rather its aim is to provide the hydrogeologist with a rudimentary understanding of how surface geophysical measurements may be of help to him. Many of the standard methods of geophysical exploration are described, but those used most extensively in ground-water investigations are stressed. The rapidly developing techniques of geophysical exploration involving measurements in the microwave, infrared, and ultraviolet portions of the electromagnetic spectrum are not included. The application of these "remote sensors" to ground-water investigations is in an early stage of development and testing; thus, their eventual importance cannot be appraised at this time. Borehole geophysical techniques will not be discussed here except as they relate to surface or airborne surveys.

In the discussions that follow each of the major geophysical methods will be briefly described with emphasis on the applications and limitations in ground-water investigations. A few examples of successful application of each method will be described.

Design of Geophysical Surveys

Geophysical surveys can be useful in the study of most subsurface geologic problems. Geophysics also can contribute to many investigations that are concerned primarily with surface geology. However, geophysical surveys are not always the most effective method of obtaining the information needed. For example, in some areas auger or drill

holes may be a more effective way of obtaining near-surface information than geophysical surveys. In some investigations a combination of drilling and geophysical measurements may provide the optimum cost-benefit ratio. Geophysical surveys are not practical in all ground-water investigations, but this determination usually can be made only by someone with an understanding of the capabilities, limitations, and costs of geophysical surveys.

A clear definition of the geologic or hydrologic problem and objectives of an investigation is important in determining whether exploration geophysics should be used and also in designing the geophysical survey. The lack of a clear definition of the problem can result in ineffective use of geophysical methods. The proper design of a geophysical survey is important not only in insuring that the needed data will be obtained but also in controlling costs, as the expense of making a geophysical survey is determined primarily by the detail and accuracy required.

Collection and Reduction of Geophysical Data

Some simple geophysical surveys can be made by individuals with little previous experience and with an investment in equipment of only a few hundred dollars. Other surveys require highly skilled personnel working with complex and expensive equipment. Good equipment and technical expertise are essential to a high quality survey. Attempts to use obsolete or "cook-book" interpretation methods in geophysical surveys often increase the total cost of the survey and result in an inferior product.

Some geophysical data can be used directly in geologic interpretations. Other geophysical data require considerable processing before the data can be interpreted, and the cost of data reduction is a major part of the total cost of the survey. Many data processing operations in use today require the use of electronic computers.

Interpretation

Interpretation of geophysical data can be completely objective or highly subjective. It can range from a simple inspection of a map or profile to a highly sophisticated operation involving skilled personnel and elaborate supporting equipment. Some interpretations require little understanding of the geology, but the quality of most interpretations is improved if the interpreter has a good understanding of the geology involved. Although some individuals are both skilled geophysicists and geologists, a cooperative effort between geologists and geophysicists is usually the most effective approach to the interpretation of geophysical data.

The Literature of Exploration Geophysics

The science, technology, and art of geophysical exploration have undergone explosive growth in the last two decades and with this growth has come an increasing degree of specialization in all subdisciplines of the field. The literature indicates an increasing trend in this direction and the geologist or engineer interested in applications of geophysics to problems with which he is concerned is faced with a growing array of books and periodicals. With the idea that interested readers of this manual may want to pursue specific subjects, a list of the more readily available texts and periodicals published in English follows. Some of them date back as many as 30 years, and parts of these are outdated. Nevertheless, much of the theory presented in them is still valid today.

Elementary Textbooks of a General Nature

Dobrin, M. B., 1960, Introduction to Geophysical Prospecting: Second ed., McGraw-Hill Book Co., Inc., New York, 446 p.

Eve, A. S., and Keys, D. A., 1956, Applied Geophysics in the Search for Minerals: Fourth ed., Cambridge University Press, London, 382 p.

Griffiths, D. H., and King, R. F., 1965, Applied Geophysics for Engineers and Geologists: Pergamon Press, London, 223 p.

Nettleton, L. L., 1940, Geophysical Prospecting for Oil: McGraw-Hill Book Co., Inc., New York, 444 p.

Parasnis, D. S., 1962, Principles of Applied Geophysics: Methuen, London, 176 p.

Advanced Textbooks of a General Nature

Grant, F. S., and West, G. F., 1965, Interpretation Theory in Applied Geophysics: McGraw-Hill Book Co., Inc., New York, 581 p.

Heiland, C. A., 1940, Geophysical Exploration, Reprinted 1963: Hafner, New York, 1,013 p.

Jakosky, J. J., 1950, Exploration Geophysics: Second ed., Trija, Los Angeles, 1,195 p.

Landsberg, H. E., ed., Advances in Geophysics: vols. 1–13, Academic Press, New York.

Books Emphasizing the Electrical Methods

Bhattacharya, P. K., and Patra, H. P., 1968, Direct Current Geoelectric Sounding—Principles and Interpretation: Elsevier, Amsterdam, 135 p.

Hansen, D. A., Heinrichs, W. E., Jr., Holmer, R. C., MacDougall, R. E., Rogers, G. R., Sumner, J. S., and Ward, S. H., eds., 1967, Mining Geophysics, Vol. II, Theory, Chapter II: Soc. Explor. Geophysicists, Tulsa, 708 p.

Keller, G. V., and Frischknecht, F. C., 1966, Electrical Methods in Geophysical Prospecting: Pergamon Press, Oxford, 517 p.

Kunetz, Geza, 1966, Principles of Direct Current Resistivity Prospecting: Gebruder Bornträeger, Berlin, 103 p.

Books Emphasizing the Seismic Method

Dix, C. H., 1952, Seismic Prospecting for Oil: Harper, New York, 414 p.

Musgrave, A. W., ed., 1967, Seismic Refraction Prospecting: Soc. Explor. Geophyisists, Tulsa, 604 p.

Slotnick, M. M., 1959, Lessons in Seismic Computing: Soc. Explor. Geophysicists, Tulsa, 268 p.

White, J. E., 1965, Seismic Waves—Radiation, Transmission, and Attenuation: McGraw-Hill Book Co., Inc., New York, 302 p.

Books Emphasizing the Magnetic Method

Hansen, D. A., Heinrichs, W. E., Jr., Holmer, R. C., MacDougall, R. E., Rogers, G. R., Sumner, J. S., and Ward, S. H., eds., 1967, Mining Geophysics, Vol. II, Theory, Chapter III: Soc. Explor. Geophysicists, Tulsa, 708 p.

Nagata, Takesi, 1961, Rock Magnetism: Rev. ed., Maruzen, Tokyo, 350 p.

Case History Compilations

European Association of Exploration Geophysicists, 1958, Geophysical Surveys in Mining, Hydrological and Engineering Projects: European Association of Exploration Geophysicists, The Hague, The Netherlands, 270 p.

Lyons, P. L., ed., 1956, Geophysical Case Histories: Vol. II–1956, Soc. Explor. Geophysicists, Tulsa, 676 p.

Nettleton, L. L., ed., 1949, Geophysical Case Histories: Vol. 1–1948, Soc. Explor. Geophysicists, Tulsa, 671 p.

Woollard, G. P., and Hanson, G. F., 1954, Geophysical Methods Applied to Geologic Problems in Wisconsin: Univ. Wisconsin, Madison, 255 p.

Periodicals

"Geoexploration," published by the Elsevier Publishing Company, Amsterdam, The Netherlands.

"Geophysics," published by the Society of Exploration Geophysicists, Tulsa, Okla.

"Geophysical Abstracts," previously published by the U.S. Geological Survey, Washington, D.C. (Publication ceased in 1971)

"Geophysical Prospecting," published by the European Association of Exploration Geophysicists, The Hague, The Netherlands.