U.S. GEOLOGICAL SURVEY CIRCULAR 987

The Use of Surface Geophysical Techniques To Detect Fractures in Bedrock— An Annotated Bibliography

Prepared in cooperation with the U.S. Department of Energy

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By Mark R. Lewis *and* F.P. Haeni

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CONVERSION FACTORS AND ABBREVIATIONS

INCH-POUND TO METRIC UNITS		
Multiply inch-pound unit	**By**	**To obtain metric unit**
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer(km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Resistivity	
Ohm-feet (ohm-ft)	0.3048	ohm-meter (ohm-m)
	Mass	
pound (lb)	0.4536	kilogram (kg)

METRIC TO INCH-POUND UNITS		
Multiply metric unit	**By**	**To obtain inch-pound unit**
	Length	
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
square kilometer (km^2)	0.3861	square mile (mi^2)
	Resistivity	
ohm-meter (ohm-m)	3.281	ohm-feet (ohm-ft)
	Mass	
kilogram (kg)	2.205	pound (lb)

The Use of Surface Geophysical Techniques to Detect Fractures in Bedrock—An Annotated Bibliography

By Mark R. Lewis and F.P. Haeni

Abstract

This annotated bibliography compiles references about the theory and application of surface geophysical techniques to locate fractures or fracture zones within bedrock units. Forty-three publications are referenced, including journal articles, theses, conference proceedings, abstracts, translations, and reports prepared by private contractors and U.S. Government agencies. Thirty-one of the publications are annotated. The remainder are untranslated foreign language articles, which are listed only as bibliographic references.

Most annotations summarize the location, geologic setting, surface geophysical technique used, and results of a study. A few highly relevant theoretical studies are annotated also.

Publications that discuss only the use of borehole geophysical techniques to locate fractures are excluded from this bibliography. Also excluded are highly theoretical works that may have little or no known practical application.

INTRODUCTION

The need for cost effective methods to locate individual fractures or fracture zones in bedrock has increased in recent years. Such methods are critical to a wide variety of hydrogeologic applications, one of the most important of which is hazardous-waste management. Bedrock fractures provide a conduit for the migration of waste from disposal areas to household or municipal wells. Information about fractures is needed to predict the movement and fate of contaminants. Surface geophysical techniques have been used successfully to locate fractures and to describe their geometry.

Another hydrologic application is the evaluation of the suitability of various geologic structures or sites for nuclear-waste repositories. Plutons in continental shield areas and salt domes have been considered for this use because of their typically low primary permeability and porosity and because of their relative tectonic stability (Wright and others, 1980; Mair and Green, 1981; Soonawala and Dence, 1981; Green and Mair, 1983; Bazinet and Legault, 1985). Granitic plutons commonly contain fractures or fracture systems that must be studied to prevent the migration of radioactive waste.

Fractured rock is a potential source of ground water in many parts of the world. Most bedrock wells depend on fractures for recharge and permeability. Information on fracture configuration can be used to help locate wells and to reduce the chances of drilling dry holes.

Many other activities require information on bedrock fractures. Fractures play a role in the stability of mines and tunnels (Stephansson and others, 1979), need to be considered in developing geothermal energy systems (Aamodt and others, 1977), and are an important factor in the in-place mining of uranium, copper, or other minerals by chemical leaching. Fractures within bedrock units typically are evaluated by surficial mapping of outcrops, by interpreting lineations on aerial or satellite photos, or by analyzing lithologic samples from boreholes. The usefulness of these methods for fracture-detection studies is limited. Fractures are not always continuous throughout a body of rock, and those present at depth may have no surface expression. In addition, unconsolidated sediment or artificial fill commonly covers the bedrock surface and limits the use of surficial-mapping techniques. Drilling is expensive and must be supplemented by other indirect methods.

The increased demand for information on fractures within a rock body, and the limited usefulness of traditional data-collection methods, has led to the development and use of new methods for gathering that information. Among the most promising developments in this area is the introduction of geophysical methods to locate and evaluate bedrock fractures.

Surface and borehole geophysical methods both have been successfully used to locate and characterize fractures in bedrock, although this report is concerned only with surface geophysical methods. A recent review of literature relating to borehole geophysical methods is presented by Paillet (1985).

Surface geophysical methods are numerous and varied, but they all measure the response of subsurface materials and their interstitial fluids to a naturally or artificially generated signal (sound, electrical current, and so forth). Interpretation of this response provides information about the subsurface materials and the fluids within them. These methods have several advantages over traditional mapping methods. Geophysical surveys generally are less expensive than drilling programs and, when conducted in conjunction with an exploratory drilling program, can reduce the number of drill holes needed by placing drill holes more effectively. Surface geophysical surveys also create little or no environmental disturbance. Therefore they may be used in areas where drilling is not allowed or is impractical. Some surface geophysical techniques also can be used to examine bedrock covered by unconsolidated material.

PURPOSE AND SCOPE

This bibliography is a compilation of references for literature describing the theory and application of surface geophysical methods to the problems of locating fractures or fracture zones in bedrock. Annotations of most references are provided to assist the reader in evaluating the relevance of the articles to a particular hydrogeologic setting.

Several sources were consulted in the compilation of this bibliography. Initially, a computerized search was made of the National Technical Information Service (NTIS) and GeoRef[1] data bases. The NTIS data base is the computerized equivalent of the U.S. Government Reports and Announcements Index. As of January 1981, the NTIS data base contained about 700,000 references to U.S. Government technical and research reports and journal articles, dating back to 1970. GeoRef, a product of the American Geological Institute, is a compilation of several bibliographies, including the "Bibliography of North American Geology," "Bibliography and Index of Geology Exclusive of North America," "Bibliography of Theses in Geology," "Geophysical Abstracts," and "Bibliography and Index of Geology." It compiles and lists articles from over 4,500 international journals and conference proceedings, books, maps, dissertations, and other publications dating back to 1785. In addition, a manual search of the previous 5 years of issues of the "Bibliography and Index of Geology" was performed, and additional references were found.

All relevant publications, except for a few untranslated foreign-language articles, were obtained for further evaluation. The reference lists of these publications were checked for additional references. This process was supplemented by a monthly check of the current "Bibliography and Index of Geology" to reference those publications indexed since the computer literature search. Several authors also were contacted to check on the current status of their work and on new publications.

Publications that discuss only borehole geophysical methods were excluded, as were highly theoretical articles having little or no known practical application. Only those articles that describe a new technique, a new variation of an existing technique, or a new use of an existing technique under novel field conditions were included in this bibliography.

To avoid the use of awkward converted units of measurement and to reduce the possibility of confusion, the units used in the original sources have been preserved in the annotations. A table of factors for converting inch-pound units to metric units and vice versa is included in this report for the reader's convenience.

This compilation includes several foreign language references that were available in fully translated form. These have been annotated and are included in the main body of this report. Those articles for which full translations could not be obtained were not annotated but are included in a section at the end of this report.

[1]Any use of trade names and trademarks in this publication is for descriptive purposes only and does not constitute endorsement by the U.S. Geological Survey.

ANNOTATED REFERENCES

Anderson, D.L., Minister, B., and Cole, D., 1974, The effect of oriented cracks on seismic velocities: Journal of Geophysical Research, v. 79, no. 26, p. 4011–4015.

This article presents a theory on the effects of fluid-filled fractures having a preferred orientation on seismic velocities within rock. The theory assumes that the fractures within a body of rock, and the mineral grains that constitute that rock, are randomly oriented. The authors conclude that seismic velocities within fractured rock are controlled by (1) the elastic properties of the matrix, (2) porosity of the rock, (3) aspect ratio of the fractures, (4) bulk modulus of the pore fluids, and (5) the direction of seismic-wave propagation. Seismic velocities are decreased in a direction normal to the plane of the cracks.

Bamford, D., and Nunn, K.R., 1979, In-situ seismic measurements of crack anisotropy in the Carboniferous limestone of northwest England: Geophysical Prospecting, v. 27, p. 322–338.

P-wave velocity anisotropy, which is defined as the variation in seismic P-wave velocity with direction, was determined from P-wave velocities measured by using 12-channel seismic-refraction equipment in Carboniferous limestone at three sites in northwestern England. The limestone, which is partly overlain by a few meters of drift, contains three dominant vertical joint sets having known orientations.

Field observations consisted of linear profiles, fan shots, and offset shots. Directional variations in P-wave velocity were correlated with "previously mapped orientations of joints." The authors suggest that the use of seismic-reflection techniques might allow measurement of velocity anisotropies over a wider range of conditions than that provided by refraction techniques.

Bazinet, Robert, and Legault, Jean, 1985, Scalar audiomagnetotellurics: A tool in the evaluation of nuclear waste disposal sites: Society of Exploration Geophysicists Annual International Meeting, 55th, Washington, D.C., 1985, expanded abstracts of the technical program with author's biographies, p. 149–150.

The scalar audiomagnetotelluric method can be used to measure indirectly the water content of fractured or porous rock by measuring the rock's apparent resistivity. This technique is a simplified version of the conventional audiomagnetotelluric method. At any given frequency, the technique measures only a single pair of the electrical and magnetic components of a naturally occurring electromagnetic (EM) field. By doing this, the expression for apparent resistivity is reduced from a complex tensor to a scalar equation; this change simplifies the interpretation process. Because the depth of penetration varies as a function of frequency, a vertical profile can be constructed.

This technique was used to locate water-filled fractures within a pluton at a potential nuclear waste-disposal site on the Canadian Shield in Ontario. Two rock layers were distinguished, on the basis of differing apparent resistivities. The top layer, which is relatively conductive, was interpreted to be a combination of glacial overburden and the fractured top of bedrock. This layer is underlain by highly resistive material, which was interpreted to be nonfractured bedrock. The article does not mention whether this model was checked against test-hole or surface-mapping data.

The authors list two advantages of this technique over other surface geophysical techniques for detecting fractures. (1) Only water-filled fractures will be detected; those filled with quartz or other minerals will be ignored. (2) Data from deep fractures can be obtained.

Crampin, Stuart, McGonigle, Robert, and Bamford, David, 1980, Estimating crack parameters from observations of P-wave velocity anisotropy: Geophysics, v. 45, no. 3, p. 345–360.

The authors mapped fractures in shallow Carboniferous limestone in northwestern England by reinterpreting seismic-refraction data obtained by Bamford and Nunn (1979). The data consisted of reversed seismic profiles up to 70 m long and fan shots having 40-m radii. The authors concluded that (1) information about fracture properties may be obtained by inverting velocity anisotropy data; (2) variations in velocity reflect different degrees of saturation within cracks; (3) if the dip of fractures can be assumed, then "inversion of only the P-wave velocity anisotropy can model the complete velocity variation of all body waves in the structure by means of effective anisotropic elastic constants"; and (4) polarization anomalies observed for synthetic seismograms indicate wave "propagation through cracked or anisotropic structures."

Denahan, B.J., and Smith, D.L., 1984, Electrical resistivity investigations of potential cavities underlying a proposed ash disposal area: Environmental Geology and Water Science, v. 6, no. 1, p. 45–49.

A direct current (D.C.) resistivity survey was performed to define solution cavities in fossiliferous Eocene limestone at a proposed ash-disposal site in Florida. The limestone, which is overlain by up to 5 ft of unconsolidated material, contains solution cavities having average diameters of 1 to 5 ft. The survey was performed on a 1,200-

by 2,600-ft grid by using a Wenner array having constant electrode spacing. At some locations, Wenner array depth soundings having systematically increased electrode spacings also were performed. Several zones of low apparent resistivity were detected, and they were attributed to fluid-filled solution cavities. Results of resistivity surveys were checked by drilling 54 test borings, 24 of which coincided with the resistivity stations. The authors reported an 86-percent agreement between data collected during drilling and interpretations of resistivity measurements.

Frolich, R.K., 1986, Size estimates of buried fracture zones with geophysical methods [abs.]: Geological Society of America, Abstracts with Programs, v. 18, no. 1, p. 17.

Gravity and magnetic surveys were used to locate fracture zones in crystalline rock in Rhode Island. The author suggests that fracture zones commonly are found beneath "valleys and topographic lows," because fractured rock is easily eroded. The gravity survey located gravity lows in the area of a lineament and in a river valley. These lows are interpreted as representing fracture zones that are 500 m wide and 1 to 4 km deep and that have porosities ranging from 2 to 4 percent. He cautions that these figures are approximations "indicating the order of magnitude rather than the precise geometry of fracture zones."

The magnetic surveys were performed over buried glacial stream channels. The surveys detected "negative anomalies which can be explained by non-magnetic gaps" associated with fracture zones. These anomalies were detectable by using station spacings of 100 ft, in areas having "extremely low and irregular levels of magnetization." Information from the magnetic surveys was correlated with "outcrop evidence and magnetic susceptibility measurements on hand samples."

Goryunov, I.I., 1972, Udelnoe elektricheskoe soporotivlenie treschinovatoi porody [Electrical resistivity of fractured rock]: U.S. Bureau of Mines Report TR-3-72, 15 p. [Translation of Prikladnaya Geofizika (USSR), no. 38, p. 173-179, 1964, Law, D.A., and Brown, J.W., translators.]

This paper describes the use of matrix algebra to derive a theoretical relation between the geometry of fractures within a rock and that rock's electrical resistance. The author made several simplifying assumptions. (1) Three randomly oriented fracture systems are assumed to cut an otherwise uniform, isotropic body of rock. (2) Each fracture system was assumed to consist of parallel fractures that extended indefinitely in two dimensions and that had identical width and regular spacing. (3) The fractures were assumed to be filled with a material having a resistivity lower than that of the surrounding bedrock.

The method can be applied in a forward or inverse direction. The resistance tensor of the fractured rock can be calculated by using the resistivity of the rock matrix and of the fluid filling the fractures, as well as by the geometry of the fractures. Conversely, the density and width of fractures can be determined if the resistance of fractured rock is known.

The width and density of fractures at a depth of approximately 2,300 m within a borehole were measured by using the methods outlined above. Resulting values were found to correspond with measurements made by microscopic examination of thin sections of the borehole core. The article did not discuss field methods used to make these measurements.

Green, A.G., and Mair, J.A., 1983, Subhorizontal fracture zones in a granitic pluton: Their detection and implications for radioactive waste disposal: Geophysics, v. 48, no. 11, p. 1428-1449.

This study used high-resolution, seismic-reflection techniques to locate horizontal fracture zones at depths up to 800 m within a granitic pluton on the Canadian Shield in southeastern Manitoba. The pluton is overlain by a discontinuous layer of highly conductive till having a maximum thickness of about 25 m. Previously, the till had hindered electromagnetic and resistivity measurements at a nearby site (Soonawala and Dence, 1981).

Data were collected along five profiles over a 4.8-km^2 area. Small construction-type earth tampers were used as a sound source for three of the profiles; explosives were used in the other two. The receiving setup consisted of 24 arrays of 9 geophones each. Each group of geophones was deployed along a 10- to 20-m line having a 10- to 20-m interval between arrays.

The surveys revealed two gently dipping reflectors, which were interpreted as fracture zones. Holes drilled along the profiles intersected major fracture zones at depths of 300 to 600 m. This observation was in close agreement with the depths predicted from the seismic profiles. Borehole-televiewer examination of one drill hole confirmed the shallow dip of the fractures.

Harmon, E.J., 1984, Investigation of a previously unexplored basaltic aquifer using complementary geophysical methods, *in* Nielsen, D.M., and Curl, M., eds., National Water Well Association/U.S. Environmental Protection Agency Conference on Surface and Borehole Geophysical Methods in Groundwater Investigations, San Antonio, Texas, 1984, Proceedings: Worthington, Ohio, National Water Well Association, p. 273–287.

This investigation focused on the Servilleta Formation—a series of Pliocene basalt flows in southern Colorado. The basalt flows, which range from 250 to 370 ft in thickness, are interbedded with thin layers of sand, gravel, clay, and minor ash flows. Major north-south-trending normal faults and associated fracture systems cut the Servilleta and produce characteristic horst and graben structures. Reworked sand, gravel, and clay deposits, which average 250 to 300 ft in thickness, overlie the basalt.

Various geophysical surveys were performed in the area as part of an exploration program to find a source of water for a coal-slurry pipeline. The results of each survey were cross-checked against the results of the other surveys and against data obtained by test drilling, aquifer testing, and conventional geologic mapping.

Data from a 3,800-ft-long seismic-refraction line were used to locate a large, previously mapped fault. This technique was less successful with smaller faults and with their associated fracture zones. The authors suggest that the refraction survey may have been "too limited" to detect the smaller scale faults and fracturing. Total-field ground magnetometer surveys, however, were more successful in locating these small-scale features. Magnetometer-survey results were confirmed by test drilling. Gradient-array and dipole-dipole resistivity surveys both were able to clearly delineate the smaller scale faults.

Huntley, D.J., and Misher, H.M., 1984, Relationship between permeability and electrical resistivity in granular and fractured rock aquifers, *in* Nielsen, D.M., and Curl, M., eds., National Water Well Association/U.S. Environmental Protection Agency Conference on Surface and Borehole Geophysical Methods in Groundwater Investigations, San Antonio, Texas, 1984, Proceedings: Worthington, Ohio, National Water Well Association, p. 18–36.

This survey was part of a project designed to examine the relation between electrical conductivity and permeability in fractured rock and unconsolidated aquifers. Permeabilities of fractured-rock aquifers, determined by pumping tests, were compared with permeabilities determined by dipole-dipole resistivity surveys. Twelve sites were examined, and 24 true-resistivity cross sections were constructed. "Distinctive vertical, low resistivity anomalies through, or immediately adjacent to" well sites were interpreted as representing clay weathering within fracture zones. At three well sites, clay weathering zones recorded in borehole logs were not detected by the resistivity survey. Fractures in the remaining four well sites intersect relatively unweathered rock. The authors suggest that the presence of such highly conductive clay minerals in the weathered zones "strongly affects the apparent formation factor in fractured rock." Formation factor is defined as the ratio of the resistivity of a fractured rock to that of the fluid that saturates the rock.

Imse, J.P., and Levine, E.N., 1985, Conventional and state of the art geophysical techniques for fracture detection: National Water Well Association Annual Eastern Regional Groundwater Conference, 2d, Portland, Maine, 1985, Proceedings, p. 18–36.

Microgravity, electrical resistivity, ground-penetrating radar, and seismic-refraction techniques were used in an attempt to delineate fracture zones within flat-lying carbonate rocks at a site in northern New York. Bedrock in the area is characterized by extensive development of karst topography and is overlain by topsoil, weathered bedrock, and artificial fill from 0 to more than 30 ft in thickness.

Seismic-refraction and ground-penetrating radar were the most successful techniques used. Information from these methods was independently verified by subsequent mapping.

The seismic surveys were conducted by using a 24-channel seismograph having 250-ft spreads and a shotgun-type sound source. Some fracture zones were indicated on the seismic profiles as distinct low-velocity zones. In areas where individual fractures are separated by intact rock, the fractures were recognized as directional variations in seismic velocities.

If a refraction line paralleled the trend of a fracture system, much of the seismic energy was conducted directly to the geophones through the intact rock between the fractures. Such a fracture system had relatively little effect on seismic velocities. If a line was perpendicular to the fracture trend, however, seismic energy had to travel across fracture openings to reach the geophones. This effect lowered seismic velocity in that direction.

Ground-penetrating radar data were collected by using a 300-MHz antenna. The data were reportedly of sufficient quality to allow interpretation with no further processing. Fracture zones were marked on the radar record as hyperbola-shaped reflections. Such features were produced when the radar signal was reflected from the sides of the fracture as the radar unit passed overhead.

Jammallo, J.M., 1984a, Delineation of bedrock fracture trace zones by remote sensing and magnetics and their hydrogeologic implications: Burlington, Vt., University of Vermont, unpublished master's thesis, 274 p.

This study integrated aerial photointerpretation with a surface geophysical survey to define fracture zones in northern Vermont. The study area, which is underlain by metamorphic rock, has a thin mantle of till at higher elevations and stratified drift and alluvial sand in valleys. Fractures, which initially were identified as linear features on aerial photographs, were located by a systematic magnetometer survey. To confirm the results of this work, joints were mapped at outcrops.

Magnetic anomalies were classified according to their origin to separate those caused by fracture zones from those resulting from magnetic mineralization or cultural interference. Most of the photolineaments caused by fracture zones were found to have strong positive magnetic anomalies. The azimuth of each anomaly was defined in the field by performing a continuous circular survey about the point of greatest intensity. Orientations thus determined were found to correspond to the directions of the photolineaments within $\pm 10°$. The joint outcrop mapping data were not analyzed statistically, although "slight positive correlation" seemed to occur between the areas of high joint density noted in the field and areas of "fracture trace concentration" defined by magnetic and photographic methods.

Jammallo, J.M., 1984b, Use of magnetics to enhance identification of bedrock fracture trace zones for well locations: National Water Well Association Annual Eastern Regional Groundwater Conference, 1st, Newton, Mass., 1984, Proceedings, p. 273–287.

This talk summarized the results reported in greater detail by Jammallo (1984a).

Kerschner, D.R., 1980, The location of fractured zones in bedrock by earth resistance, seismic refraction, and soil temperature surveys [abs.]: Geological Society of America, Abstracts with Programs, v. 12, no. 2, p. 45.

This study used seismic-refraction, resistivity, and subsurface-temperature measurements to locate fractures in bedrock overlain by till. Fracture zones were denoted as areas of lowered seismic velocity and resistivity. In addition, the temperature 4 ft below land surface, near the fracture zone, was more stable over the course of the experiment than that in the surrounding area. This effect was attributed to moist material within the fracture zone acting as a heat sink. The results from each of the three methods were in close agreement.

Kirk, K.G., and Rauch, H.W., 1977, Location of fracture zones by electrical resistivity surveying with the tri-potential resistivity technique [abs.]: Eos, Transactions of the American Geophysical Union, v. 58, no. 6, p. 392.

The tri-potential resistivity technique integrates data from three commonly used resistivity sounding arrays: CPPC (current-potential-potential-current electrode arrangement), CPCP (current-potential-current-potential electrode arrangement), and CCPP (current-current-potential-potential electrode arrangement). This method was applied to locate fractures in shale-sandstone rocks at an underground coal gasification plant in West Virginia. Fracture zones and their corresponding resistivity anomalies were delineated by plotting apparent resistivities and percentage residual resistivities. Percentage residual resistivity is equal to $(R_{CPPC}-R_{CCPP}-R_{CPCP}) \times$

($100/R_{CPPC}$), where R_{CPPC} is equal to apparent resistivity measured by the current-potential-potential-current electrode arrangement, R_{CCPP} is equal to apparent resistivity measured by current-current-potential-potential electrode arrangement, and R_{CPCP} is equal to apparent resistivity measured by the current-potential-current-potential electrode arrangement.

Six fracture zones were located, four of which correspond to mapped photolineaments. The percentage-residual-resistivity measurement was reportedly able to detect the location, surface width, and minimum depth of the fracture zones.

Leonard-Mayer, P.J., 1984a, A surface resistivity method for measuring hydrologic characteristics of jointed formations: U.S. Bureau of Mines Report of Investigations 8901, 45 p.

The azimuthal-resistivity method may be used to determine the strike direction of the dominant set of fractures or joints within bedrock. In this technique, Wenner, Lee, and Wenner-Lee arrays are rotated about a fixed point, and current-potential readings are taken at fixed intervals of rotation (commonly 10°). The resulting apparent resistivity readings, when plotted on polar coordinate axes, approximately define an ellipse. Strike direction of fractures and joints may be determined from the graph by noting directions of high apparent resistivity. This method assumes that joints or fractures may be treated as thin layers having resistivities that contrast with those of the surrounding rock.

This method was applied in carbonate rocks at four sites in Minnesota and Wisconsin and in shale at a coal mine in Pennsylvania. Wenner and Wenner-Lee arrays were used in all surveys. Because structural patterns in the rocks at each of the sites are known from previous work, results of the surface geophysical surveys could be confirmed. The Wisconsin sites also were examined in a separate study by Taylor (1982, 1984), and the Minnesota site was the subject of a similar survey by Technos, Inc. (1985).

The resistivity surveys were notably successful in locating water-filled joints and fractures but could not locate those filled with air. Water within joints and fractures creates a zone of increased conductivity (decreased resistivity). In air-filled fractures, the direction of maximum apparent resistivity varies over time. This effect is attributed to differential drying of the fractures in the rock. At the Pennsylvania site, survey results were in good agreement with fracture orientation, whereas "the effect of joints was much less obvious." A horizontal-resistivity survey was run along the length of a valley at this site by using a Wenner-Lee array having a constant survey orientation. Zones of low apparent resistivity encountered along this line are thought to represent zones of increased fracturing.

Water flowing from a river through fractures and into the mine at the Pennsylvania site caused measurable streaming potential. Drops in the streaming potential were found to correspond well with fracture and joint strike determined by the azimuthal resistivity method.

Leonard-Mayer, P.J., 1984b, Development and use of azimuthal resistivity surveys for jointed formations, *in* Nielsen, D.M., and Curl, M., eds., National Water Well Association/U.S. Environmental Protection Agency Conference on Surface and Borehole Geophysical Methods in Groundwater Investigations, San Antonio, Texas, 1984, Proceedings: Worthington, Ohio, National Water Well Association, p. 52–91.

This talk summarized the results reported in greater detail by Leonard-Mayer (1984a).

Mair, J.A., and Green, A.G., 1981, High resolution seismic reflection profiles reveal fractures within a homogeneous granite batholith: Nature, v. 294, p. 439–442.

This paper summarizes the results reported later in greater detail by Green and Mair (1983).

Mallik, S.B., Bhattacharya, D.C., and Nag, S.K., 1983, Behaviour of fractures in hard rocks—A study by surface geology and radial VES method: Geoexploration, v. 21, p. 181–189.

The radial VES (vertical electrical sounding) method was employed to detect fractures within amphibolites, metabasics, and granites at five sites in West Bengal, India. This study employed a Schlumberger array, which was rotated about each sounding station. Apparent-resistivity measurements were made at 45° intervals and were plotted on polar diagrams. In a perfectly isotropic medium, the resulting plot would be circular. Apparent resistivities from these sites plotted as ellipses; the ellipsoid plots indicate anisotropic conditions and rock fractures. The orientation of the major axis of an ellipse indicates the strike direction of the corresponding fracture.

To confirm the results of the VES survey, fracture orientations were mapped at about 100 outcrops. The results were plotted on an equal-area net and were found to be in good qualitative agreement with the VES data. Both methods detected fracture systems striking in similar directions. The paper does not discuss the specific quantitative accuracy of the VES technique.

Moore, D.L., and Stewart, M.T., 1980, Geophysical signatures to fracture traces in west-central Florida [abs.]: Geological Society of America, Abstracts with Programs, v. 12, no. 4, p. 202.

Infrared aerial and satellite photographs were used to locate fracture traces in carbonate rocks in west-central Florida. The fracture zones are approximately 1 to 3 km long and 200 to 300 m wide. The traces were successfully located in the field by using seismic-refraction and electrical-resistivity techniques. Magnetic surveys were unsuccessful, and highly accurate gravity surveys were found to require "further investigations... to determine their practical value" in this application.

Ogden, A.E., and Eddy, P.S., Jr., 1984, The use of tri-potential resistivity to locate fractures, faults and caves for siting high yield water wells, *in* Nielsen, D.M., and Curl, M., eds., National Water Well Association/U.S. Environmental Protection Agency Conference on Surface and Borehole Geophysical Methods in Groundwater Investigations, San Antonio, Texas, 1984, Proceedings: Worthington, Ohio, National Water Well Association, p. 130–149.

In the tri-potential resistivity method, three different current-potential readings are taken at each survey station. In addition to the standard CPPC array, the CCPP and CPCP arrays are moved in a lateral traverse having a constant electrode spacing throughout the traverse.

This method was applied to locate fractures, solution cavities, and faults in carbonate rock in Arkansas. Fractures and solution cavities located by resistivity surveys were confirmed either directly by well logs or by observation of outcrops or indirectly by noting unusually productive wells in the vicinity of the fractures. The following general relations were observed in this study: (1) Water-filled fractures and caves caused apparent resistivity to decrease in the CPPC and CPCP configurations and to increase in the CCPP configuration. (2) Air-filled fractures caused apparent resistivity to increase in the CPPC and CPCP configuration and to decrease in the CCPP configuration. (3) Air-filled caves caused an increase in apparent resistivity in all three configurations. The authors note that this technique may be used to detect fracture zones not mappable from aerial photographs.

Palmer, S.P., 1982, Fracture detection in crystalline rock using ultrasonic reflection techniques: Berkeley, Calif., University of California, Berkeley, PhD thesis, 338 p.

This article describes the use of high-frequency, seismic-reflection techniques to detect fractures within granite in field and laboratory settings. Measurements were made by using both P- (compressional) and SH- (horizontally polarized shear) waves.

The laboratory experiments used small piezoelectric plates as ultrasonic sources and receivers. These plates were attached to the surface of experimental specimens by epoxy. The sound sources were excited with a step-voltage pulse. The resulting seismic waves were transmitted through the granite slab to the receivers. Signals from the receivers were processed by using a variety of techniques, including deconvolution and direct-array synthesis.

Fractures present within the rock were detected as hyperbola-shaped SH-wave reflections. Dip angles of the fractures were calculated from SH-wave velocity, source-receiver separation distance, and SH-wave arrival times at two separate receivers. Interference from Rayleigh waves made detecting fractures with unprocessed P-wave signals difficult. The author suggests that both P- and SH-wave reflection measurements are needed to reliably determine whether fractures are filled with air or water.

Field work was performed in a granite quarry in Madera County, Calif. Only SH waves were measured. The piezoelectric source and receivers were attached to the rock surface by 1/2-inch bolts and a piece of lead foil coated on both sides with a sticky resin. The rock surface in the contact area was ground smooth to provide better acoustical coupling. Because of its bulk, the signal processing equipment could not be brought into the field. Instead, receiver signals were recorded on tape in analog form and were later played back and processed in the laboratory.

SH waves were found to be totally reflected by fractures. This phenomenon prevented the detection of fractures beyond the one nearest to the SH-wave source. In addition, water saturation increased attenuation of SH waves. These effects were confirmed by further laboratory experiments.

Park, Stephen, and Simmons, Gene, 1982, Crack induced velocity anisotropy in the White Mountains, New Hampshire: Journal of Geophysical Research, v. 87, no. 84, p. 2977–2983.

Azimuthal variations in seismic P-wave velocity can be used to detect fractures in rock. Such variations may be observed by using a series of rotated seismic lines that radiate from a common endpoint. This technique was tested at four sites in the White Mountains of New Hampshire. The sites are underlain by granite, quartz syenite, and volcanic rocks having discontinuous overburden up to 3 m in thickness. Measurements were made by using a 12-channel seismograph. Geophone spacing was 6 m, and rotation between lines was 20°. A 70-kg dropped weight and a sledgehammer served as sound sources.

Fracture orientations measured by this method were within 30° of the actual orientations measured directly. The authors suggest that this relatively large discrepancy may have been caused by microcracks having a preferred orientation different from that of the main fracture system. This method was unable to distinguish the effects produced by the fractures from those related to the much smaller microcracks. The authors suggest that better results might be obtained by combining measurements of S-wave velocity anistropy with measurements of P-wave velocity anisotropy.

Soonawala, N.M., and Dence, M.R., 1981, Geophysics in the Canadian nuclear waste program—A case history: Society of Exploration Geophysicists Annual International Meeting, 51st, Los Angeles, Calif., 1981, Proceedings, p. 83–98.

A variety of airborne, ground-based, and borehole-geophysical surveys was performed at the planned site of an underground laboratory in a granitic pluton in the Canadian Shield in Canada. The objectives of the surveys were to define the size of the pluton, to identify and locate fractures and other structural discontinuities within it, and to predict the pluton's long-term tectonic stability. A separate, high-resolution, seismic-reflection survey also was performed at a nearby site within the pluton (Mair and Green, 1981; Green and Mair, 1983).

Fractures visible in outcrops within a 3.8-km^2 area were mapped. A strong correlation was noted between the mapped fracture traces and results of the ground-based gradient resistivity survey. Areas having low-fracture density were found to coincide with areas of high resistivity (greater than 10,000 ohm-m). Areas having high-fracture density coincided with resistivity lows (less than 2,000 ohm-m).

Although highly conductive overburden hindered very low frequency (VLF) surveys, some trends on the VLF map may indicate major vertical fracture zones. These trends agree "reasonably well" with mapped fracture traces and results of resistivity surveys.

Stephansson, Ove, Lande, G., and Bodare, A., 1979, A seismic study of shallow jointed rocks: International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts, v. 16, p. 319–327.

This paper develops a theory for seismic-wave propagation at shallow depths in jointed rocks. According to the theory, point-source elastic waves will propagate around the tip of an open joint, where the waves will be refracted according to Huygen's principle. This propagation causes the velocity curve to be displaced along the time axis of a traveltime diagram. The resulting intercept time is used with wave velocity and joint spacing to calculate depth to the joint.

The theory was applied to determine the depth of artificial joints in concrete-block laboratory models and of natural joints at two sites in Sweden. The concrete blocks, each of which contained from 2 to 20 joints, were tested by using a pulse generator having a swinging metal head as a sound source. According to the authors, "the calculated depth of jointing is in good agreement" with actual joint depth.

Field tests were performed by using an explosive-filled, hollow-cylinder energy source. Experimentally determined depths of joints within a granitic gneiss were less than the actual depths measured directly on the face of a pit within the gneiss. This effect was attributed to deformation of the joints by a horizontal stress field within the rock body. At the other field site—an underground magnetite mine—the theoretically determined joint depth averaged 0.5 m, which is within the 0.3- to 0.8-m depth range where the majority of joints were actually found.

Taylor, R.W., 1982, Evaluation of geophysical surface methods for measuring hydrological variables in fractured rock units: U.S. Bureau of Mines Research Contract Report, contract H0318044, 147 p.

Fractured bedrock was examined at two sites in southeastern Wisconsin by using the azimuthal resistivity technique, together with seismic-velocity and attenuation measurements. The sites are underlain by a Silurian dolomite, which unconformably overlies an Ordovician sandstone. At one of the sites, an oolitic iron formation is present between the shale and the dolomite. A thin (0- to 5-ft thick) layer of till overlies the bedrock. These sites were studied also by Leonard-Mayer (1984a, b) and by Taylor (1984).

The azimuthal resistivity surveys were performed by using Wenner and Lee arrays rotated about a fixed point. Apparent resistivity readings were taken at 10° intervals, and constant *a* spacings were maintained. The results were plotted as apparent resistivity ellipses. The major axes of the ellipses correspond with the direction of primary joint strike within approximately 5°, whereas the secondary joint set had no effect on the resistivity ellipse.

Vertical movement of rainwater through the ground was detected by continuously monitoring a depth-sounding array. This apparatus incorporated a microcomputer and permanently emplaced electrodes.

Seismic data were collected by using a 6-channel seismograph and a sledgehammer sound source. P-wave first-arrival times and attenuation of P-wave first breaks and Rayleigh wave peaks were recorded as a function of azimuth. These measurements did not provide any useful information.

The authors concluded that, by analyzing the electrical resistivity measurements, they were able to determine the primary strike of joints without further field work. The seismic measurements were judged to be of no value for this application.

Taylor, R.W., 1984, The determination of joint orientation and porosity from azimuthal resistivity measurements, *in* Nielsen, D.M., and Curl, M., eds., National Water Well Association/U.S. Environmental Protection Agency Conference on Surface and Borehole Geophysical Methods in Groundwater Investigations, San Antonio, Texas, 1984, Proceedings: Worthington, Ohio, National Water Well Association, p. 37–49.

At two sites in Wisconsin, azimuthal resistivity surveys were used to determine strike and porosity of joints in a Silurian dolomite overlain by approximately 2 m of till. These sites were examined also by Taylor (1982) and by Leonard-Mayer (1984a, b). The major axis of the resistivity ellipse defined in this survey corresponded with the primary strike direction of the joints, as previously determined by other means. Joint porosities determined from the resistivity survey were within approximately 2 percent of the porosities as determined by gravity and seismic methods. The author concluded that the azimuthal resistivity method can be used successfully to determine the geometry and porosity of joint patterns within bedrock.

Technos, Inc., 1985, Hydrogeologic investigation of the Ironwood Landfill, Spring Valley, Minnesota: Miami, Fla., Technos, Inc., 88 p.

EM (electromagnetic conductivity) and resistivity-sounding surveys were used to evaluate fluid flow through a fractured rock aquifer at a hazardous-waste landfill near Spring Valley, Minn. This landfill was the site of similar work by Leonard-Mayer (1984a, b). The study area is underlain by Ordovician and Devonian shales and carbonates that are covered by discontinuous unconsolidated sediments up to 15 ft in thickness. The upper 1 to 10 ft of bedrock is weathered to sand- and silt-sized particles, whereas the deeper units are cut by fractures and solution features. In addition, extensive karst topography was observed near the site.

The EM surveys traversed a total of 15 linear miles and penetrated to depths of 20, 50, and 100 ft. Nine resistivity soundings were made by using a Wenner array. Fractures were recognized as linear areas of increased conductivity (decreased resistivity) in both the EM and resistivity-sounding surveys. Water within the fractures caused the increased conductivity. This effect was further enhanced by the presence of landfill leachate within the water. Many of the linear anomalies observed in this survey were correlated with previously observed photolineaments or with other features that indicate fracture zones.

Ulriksen, C.P.F., 1982, Application of impulse radar to civil engineering: Hudson, N.H., Geophysical Survey Systems, Inc., 179 p.

Impulse radar has been used by engineers and geophysicists for applications as widely varied as detecting salt damage in highway concrete and detecting fractures in bedrock. This type of radar transmits energy over a wide spectrum of frequencies rather than over a single frequency. Subsurface targets are located by their contrasting electrical properties. Highly resistive materials, such as most types of rock, are relatively transparent to radar waves and allow deep penetration. Radar waves will not penetrate highly conductive materials such as clay, shale, metallic ores, or rock having conductive ground water.

This technique was successfully applied to detect fractures in a granodiorite in Sweden. Two fracture zones were detected at a depth of 10 m, and their locations were confirmed by borehole observations. Impulse radar has been used also to detect a horizontal bedding plane approximately 3 m beneath the surface at a quarry in Sweden. The lithology of the rock is not specified. The radar record from this site is strikingly similar to a photograph of the quarry face.

Wire, J.C., Hofer, J.K., and Moser, D.J., 1984, Ground magnetometer and gamma ray spectrometer surveys for groundwater investigations in bedrock, *in* Nielsen, D.M., and Curl, M., eds., National Water Well Association/U.S. Environmental Protection Agency Conference on Surface and Borehole Geophysical Methods in Groundwater Investigations, San Antonio, Texas, 1984, Proceedings: National Water Well Association, p. 288–315.

This paper describes how ground magnetometer and gamma-ray spectrometer surveys were used to locate faults, contacts, weathering zones, and fracture zones within bedrock at several sites in California. Water migrating through bedrock fractures oxidizes magnetic minerals and decomposes rock-forming minerals. The effects of these processes are revealed in magnetometer surveys as magnetic lows. The alteration zone also becomes depleted in some radioactive elements; this depletion causes anomalous total gamma-ray counts. Surveys of this type are reportedly most useful in felsic igneous and metamorphic rock and may be useful also in fractured sandstone. Results in fractured shale, or in more complex sedimentary environments such as dipping beds, are "more difficult...to evaluate."

Surveys performed at a site in the Sierra Nevada batholith revealed magnetic and gamma-ray lows that suggest the presence of a fracture zone. This information was supplemented by observations at outcrops and by geological maps. A VLF survey was used with a resistivity sounding survey to locate a productive well within the fracture zone.

Wright, C., Lam, C.P., and Johnston, M., 1980, Seismic wave velocities in a rock body at Chalk River, Ontario, and their relationship to fractures [abs.]: Eos, Transactions of the American Geophysical Union, v. 61, no. 17, p. 361.

This survey detected fractures within crystalline rock at Chalk River, Ontario, by measuring seismic P- and S-wave velocities within the rock. Sound sources included a mechanical hammer and a shear wave gun. Surface and borehole geophones were used for recording. The surveys consisted of three shallow reflection lines up to 1.3 km long. Different seismic velocities noted were attributed to wave propagation through fractured gneiss and quartz monzonite and thin sheets of gabbro.

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Ikeda, K., 1980, Property and seismic wave velocity of fractured zones: Butsuri-Tanko, v. 33, no. 3, p. 34–41. [In Japanese, with English summary.]

SUMMARY

During the past decade, the number of published reports on the application of surface geophysical techniques to detect fractures in rock has increased. This bibliography contains only 8 references published from 1972 through 1978, but 10 are listed in 1984. No references before 1972 were located. Many of the early articles listed were published in foreign languages, notably Russian, whereas the majority of the more recent articles are in English.

The most widely used techniques for fracture detection have been the various D.C. resistivity, seismic-reflection, and seismic-refraction methods. These methods have been used in a wide variety of geologic settings, in straight line and in rotating-array surveys. In the straight line surveys, measurements are made along a line having a constant azimuth. Fractures or fracture zones are detected as lateral anomalies in the geophysical property being measured. In rotating-array surveys, the arrays are rotated about a fixed point, and geophysical measurements are made at fixed intervals of rotation. Fractures or fracture zones are detected as directional variations in the geophysical parameter being measured. The most common rotating-array method has been the azimuthal-resistivity survey.

A number of other surface-geophysical techniques have been used to detect and characterize fractures, including magnetometer and gravity surveys, VLF surveys, ground-penetrating radar, gamma-ray spectrometry, and subsurface temperature measurements. None of these methods have been as widely applied as the various D.C. resistivity and seismic techniques.

Although the use of surface geophysical methods to detect bedrock fractures has increased, most of the reported studies are experimental in nature. No one has reported widespread use of these methods in a routine production mode. Most of the surveys currently being performed are still designed to improve understanding of a particular method or to prove that the method works, rather than to acquire data to help solve a real problem in the field.

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Green, A.G., and Mair, J.A., 1983, Subhorizontal fracture zones in a granitic pluton: Their detection and implications for radioactive waste disposal: Geophysics, v. 48, no. 11, p. 1428–1449.

Mair, J.A., and Green, A.G., 1981, High resolution seismic reflection profiles reveal fractures within a homogeneous granite batholith: Nature, v. 294, p. 439–442.

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GLOSSARY

Acoustic coupling. The efficiency with which seismic energy is transmitted to a geophone.

Analog. (1) A continuous physical variable, such as voltage produced by a geophone, which bears a direct relation to another variable, such as motion of the Earth produced by a seismic wave, so that one is proportional to the other. (2) Continuous, as opposed to discrete or digital.

Array. (1) Electrical. The arrangement of electrodes used in electrical surveys. Also called configuration. There are many different arrays, including Wenner, Lee, Schlumberger, gradient, dipole-dipole, and so on. (2) Electromagnetic. An arrangement of antennas. (3) Seismic. The arrangement or pattern of a group of geophones or source points.

Aspect ratio. The ratio of a fracture's length to its width.

Apparent formation factor. The ratio of the measured resistivity of a 100-percent saturated formation to the resistivity of the water with which the formation is saturated.

Apparent resistivity. The resistivity of homogeneous isotropic ground that would give the same voltage-current relation as that measured in the field.

Attenuation. A reduction in amplitude or energy of a seismic or electromagnetic wave caused by the physical characteristics of the transmitting media or system.

Audiomagnetotelluric method (AMT). A method in which subsurface resistivity is determined by simultaneously measuring the orthogonal components of naturally occurring horizontal electric and magnetic fields as a function of frequency. This method uses energy in the audio (10 to 10,000 Hz) range. The energy is produced as a result of lightning discharges.

Azimuthal resistivity array. A dipole-dipole array that is rotated about the survey point to map variation with direction of apparent resistivity.

Borehole televiewer. A well log in which a pulsed, narrow acoustic (sonar) beam scans the borehole wall in a tight helix as the tool moves upward. The amplitude of the reflected wave is displayed on a cathode ray tube and reveals fractures and other discontinuities in the side of the borehole.

Bulk modulus (K). The ratio of stress to strain in a system under simple hydrostatic pressure.

Conductance. For direct current, the reciprocal of resistance, for alternating current, the resistance divided by the impedance squared. Measured in siemens (S), or mhos, which are the inverse of ohms.

Conductivity (specific conductance). The ability of a material to conduct electrical current, measured in S/m or mhos/m. In an isotropic material, equals the inverse of resistivity, in ohm/m.

Critical angle. The angle of incidence at which the refracted ray grazes the surface of contact between two media of differing seismic velocities. (It is significant only when V_2 is greater than V_1.)

Cultural interference. Interference with geophysical measurements due to manmade sources, such as powerlines, buried pipelines, fences, and so on.

Deconvolution. A process designed to restore a waveshape to the form it had before it underwent linear filtering.

Depth sounding. Measurements of a seismic or electromagnetic property as a function of depth.

Digital. The representation of information as a series of discrete numbers (rather than in analog form, where information is represented as a continuous flow of the quantity constituting the signal).

Fan shooting. A seismic-refraction technique in which geophones are located along the arc of a circle.

Forward modeling. Prediction of the geophysical measurements that would be observed by a given technique by using a hypothetical Earth model.

Fracture. A break in rock along which no appreciable movement has occurred.

Gamma-ray spectrometer. A device that measures gamma rays produced by radioactive elements. By measuring the energy levels of gamma rays, the device can determine which element is the source of the rays.

Geophone. A sensitive device used to transform seismic energy into electrical voltage for input to a seismograph.

Gravity survey. A survey that measures the strength of the gravitational field at various points in an area.

Ground-penetrating radar. A system that transmits pulses of radar energy into the ground to map geologic structures.

Huygen's principle. A concept stating that every point on an advancing wavefront can be regarded as the source of a secondary wave.

Inverse modeling. A technique that determines an Earth model that can produce geophysical measurements observed in the field.

Joint. A fracture in rock, generally more or less vertical or transverse to bedding, along which no appreciable movement has occurred.

Magnetometer. An instrument to measure the strength of a magnetic field. It measures the vertical or horizontal component of a field or the total field.

Photolineament. A linear feature visible on aerial or satellite photographs that differs significantly from the patterns in the surrounding area. It is presumed to reflect a subsurface feature.

P wave (compressional wave). An elastic body wave in which particle motion is in the direction of propagation.

Rayleigh wave. (1) A type of seismic wave propagated along the free surface of a semi-infinite medium. Particle motion near the surface is elliptical and retrograde in the vertical plane containing the direction of propagation. (2) A wave similar to (1), but the medium is not semi-infinite. (3) A tube, or surface wave, that propagates within a borehole.

Reflector. (1) **Seismic.** A contrast in acoustical impedance between two subsurface units that causes acoustic energy to be reflected. (2) **Electromagnetic.** A contrast in electrical properties that causes electromagnetic waves to be reflected.

Refractor. A layer having higher seismic velocity than that of overlying layers through which a seismic wave travels and is refracted.

Residual resistivity. The difference between the locally observed resistivity and the regional resistivity.

Resistance. Opposition to the flow of direct current, measured in ohms. The inverse of conductance.

Resistivity (specific resistance). The property of a material that resists the flow of electrical current, measured in ohm-meters. The inverse of conductivity.

Scalar. A number that is not associated with a specific direction.

Seismic-reflection method. A seismic method in which measurements are made of the arrival times of seismic waves that have been reflected from interfaces where changes in acoustical impedance occur.

Seismic-refraction method. A seismic method that incorporates seismic waves that enter a high-velocity medium near the critical angle and travel through that medium nearly parallel to its surface. The measured arrival times of the refracted waves are an indicator of the depth to each refractor.

Seismic velocity. The propagation rate of a seismic wave, without reference to direction.

Streaming potential. Voltage resulting from flow through the ground of fluid that contains ions.

Synthetic seismogram. An artificial seismic record created by assuming that a particular waveform travels through a hypothetical model of the Earth.

Tensor. A set of quantities that relates different vector fields within a vector. Usually expressed as a matrix.

Total-field ground magnetometer survey. A ground-based magnetometer survey in which the total magnetic field is measured rather than its horizontal or vertical components.

Traveltime diagram (time-distance diagram). A plot of the arrival time of refraction seismic waves as a function of the distance from the shotpoint to the geophone.

Tri-potential resistivity. A resistivity survey method in which three different electrode arrays are used together.

Vector. A quantity having both a magnitude and a direction.

Vertical profile. Measurements of the response of a geophone at various depths in a borehole to shots on the surface.

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