

Rock and Paleomagnetic Investigations

Technical Detailed Procedure GPP-06

NNWSI Project Quality Assurance Program

U.S. Geological Survey

Effective Date: November 1, 1984

UNCONTROLLED

Joseph Rosenbaum
Prepared by: Joseph Rosenbaum

Sept. 25, 1984
Date

Richard J. Reynolds
Technical Reviewer: Richard Reynolds

Sept. 25, 1984
Date

Adel Zohdy
Branch Chief: Adel Zohdy

Oct. 1, 1984
Date

W. Dudley
for NNWSI Project Coordinator: W. Dudley

Oct. 17, 1984
Date

Peter L. Bussolini
Quality Assurance: P. L. Bussolini

October 24, 1984
Date

Rock and Paleomagnetic Investigations

1.0 PURPOSE

- 1.1 This procedure provides a means of assuring the accuracy, validity, and applicability of the methods used to determine paleomagnetic and rock magnetic properties.
- 1.2 The procedure documents the USGS responsibilities for quality assurance training and enforcement, the processes and authority for procedure modification and revision, the requirements for procedure and personnel interfacing, and to whom the procedure applies.
- 1.3 The procedure describes the system components, the principles of the methods used, and the limits of their use.
- 1.4 The procedure describes the detailed methods to be used, where applicable, for system checkout and maintenance, calibration, operation and performance verification.
- 1.5 The procedure defines the requirements for data acceptance, documentation and control; and provides a means of data traceability.
- 1.6 The procedure provides a guide for USGS personnel and their contractors engaged to determining paleomagnetic and rock magnetic properties and a means by which the Department of Energy (DOE) and the Nuclear Regulatory Commission (NRC) can evaluate these activities in meeting requirements for the NNWSI repository.

2.0 SCOPE OF COMPLIANCE

- 2.1 This procedure applies to all USGS personnel, and persons assigned by the USGS, who perform work on the procedure as described by the work activity given in Section 1.1, or use data from such activities, if the activities or data are deemed by the USGS Project Coordinator to potentially affect public health and safety as related to a nuclear waste repository.
- 2.2 The procedure also applies to any contractor performing such activities for the USGS.
- 2.3 All data and interpretations from the procedure to determine paleomagnetic and rock magnetic properties presented in support of the NNWSI Project, and any calibrations or recalibrations required shall be in accordance with this Technical Detailed Procedure and will vary from it only if and when this procedure is formally revised.

3.0 PERSONNEL REQUIREMENTS AND RESPONSIBILITIES

USGS personnel and their contractors assigned to the activities and responsibilities of this procedure shall meet the requirements for technical training, experience, and personal skills, as determined by the Principal Investigator, or their designated alternates. USGS personnel assigned the responsibility of the activities of this procedure shall become familiar with details of the following USGS Quality Assurance documents:

QA Program Plan: NWM-USGS-QAPP-01, R1

QA Procedures: NWM-USGS-QP-01 to 10, R1

Unit Task Procedure: NWM-USGS-UTP-02, R0

- 3.1 The USGS NNWSI Project Coordinator shall have overall responsibility for assuring that the activities described herein are performed in accordance with this procedure.
- 3.2 The Principal Investigator for the work described under this procedure shall have direct responsibility for management and quality of said investigations and measurements conducted by the USGS for the NNWSI Project, and for the proper use of data derived from these activities.
- 3.3 The Branch Chief assigned to the responsibilities for activities, as described in this procedure by the USGS for the NNWSI Project, shall have the immediate responsibility for supervising the performance of this technical procedure for the USGS, and for the proper use of data derived from these activities.
- 3.4 The Quality Assurance Office of the USGS NNWSI Project shall have direct responsibility for the appropriate quality assurance training for USGS personnel and their contractors assigned to conduct work within the scope of this procedure.

4.0 DETAILED PROCEDURE

This procedure is used to determine the directions and intensities of remanant magnetism and susceptibilities of samples taken for the NNWSI. These magnetic properties are used to aid interpretations of geologic structure (and its genesis), volcanic stratigraphy, and magnetic anomalies.

4.1 Objective

The objective is to provide to the NNWSI the rock magnetic property data to aid interpretation of the test site stratigraphy, structure, aeromagnetic surveys and in-hole magnetic field and susceptibility logs.

4.2 Basis of the Procedure

Many rocks acquire a remanent magnetization parallel to the geomagnetic field at the time of formation (Nagata, 1961). The intensity of magnetization and magnetic susceptibility depend on a variety of factors mainly including the intensity of the magnetic field, the grain size, and the composition of the magnetic phases (Nagata, 1961).

4.3 Methods Used

4.3.1 Sample collection from outcrop

Samples are collected from the outcrop by drilling with a 0.98 in. ID diameter diamond core bit powered by a gasoline engine. The method of drilling and sample orientation is similar to that described by Doell and Cox (1967). The method used by this procedure differs in that 1) the azimuth recorded is that of the horizontal in the X-Z plane (see Fig. 4 Doell and Cox, 1967) rather than the direction of the +Y axis; 2) arrows are placed on both sides of the scribe line pointing in the -Z direction rather than short lines toward the +Y direction; and 3) the marks are placed on the specimen with indelible ink rather than with a diamond scribe. Azimuthal orientation is always obtained with a magnetic compass. In addition, a sun compass is often employed (Creer and Sanver, 1967).

4.3.2 Sample collection from drill core

Samples are collected by drilling plugs from drill core segments with a 0.98 in. ID diameter diamond core bit. The procedure for maintaining orientation between the core segments and the paleomagnetic samples is detailed below. For the geometric relationships between the core segment and the paleomagnetic specimen, see Figure 1.

Step 1: A reference line of indelible ink is placed on the core segment to be sampled parallel to the core axis. If the core was taken with an orienting barrel then the reference groove is used as the reference line.

Step 2: A piece of gridded mylar is taped to the core segment so that one set of grid lines parallels the reference line.

Step 3: The core segment is clamped in a vise with the core axis horizontal and the reference line upwards. The grid lines on the mylar are used to center the reference line between the opposing jaws of the vise so that the plane defined by the reference line and the core axis is vertical.

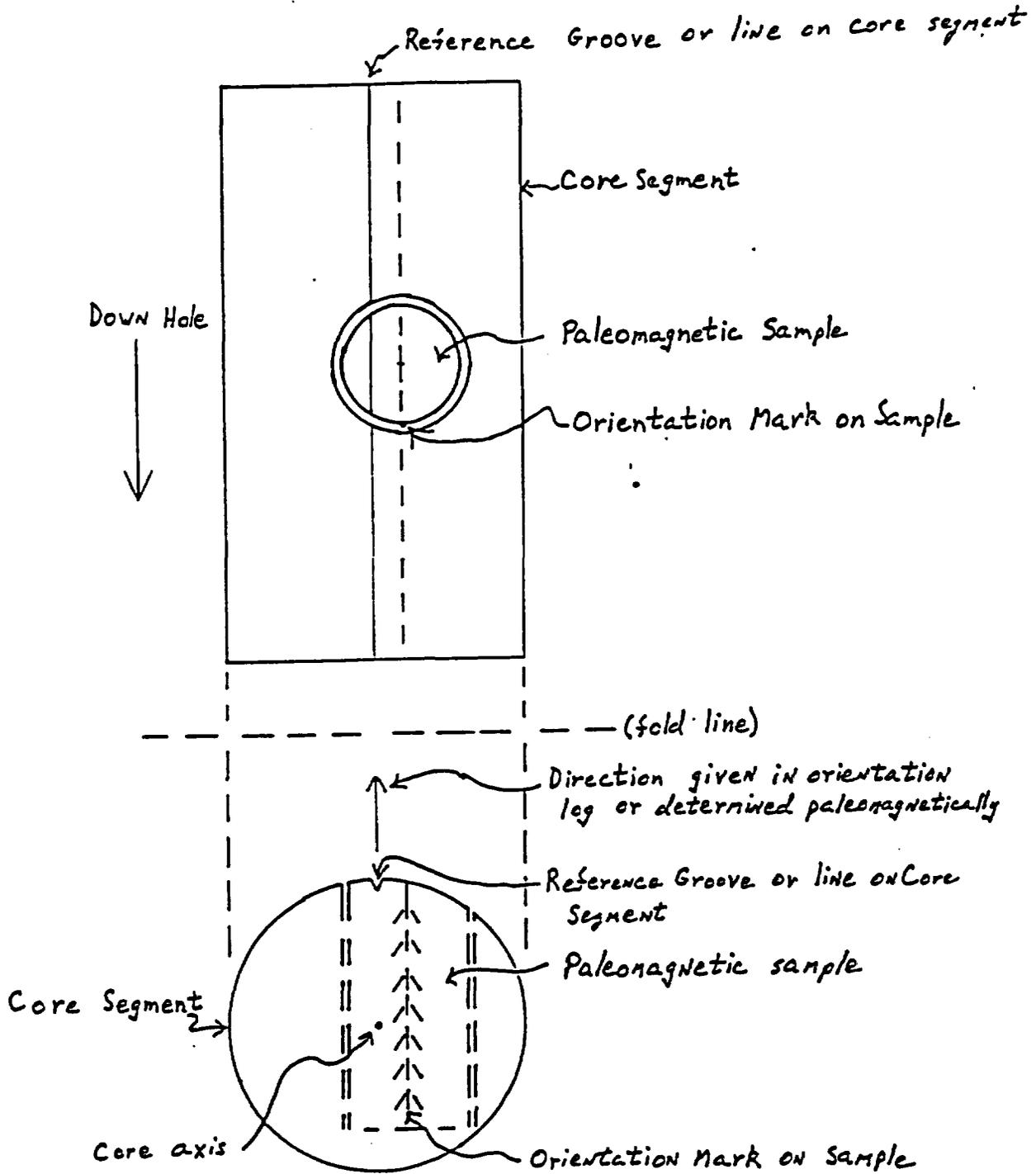


Figure 1. Geometric relationships between the core segment and the paleomagnetic samples.

Step 4: The vice and core segment are placed on a drill press and a cylindrical paleomagnetic sample is drilled so that its axis is vertical (i.e., parallel to the plane of the reference line and the core axis and normal to the core axis - see attached figure).

Step 5: An orientation line is placed on the downhole side of the paleomagnetic sample with a brass or copper rod so that the plane defined by the orientation line and the sample axis parallels the plane defined by the reference line and the core axis.

Step 6: The paleomagnetic sample is broken free of the core. Arrows pointing out of the sample hole are placed on either side of the orientation line with indelible ink.

Step 7: An identifying sample number consisting of an abbreviated drill hole identification and a depth in feet is affixed to the sample (i.e., "GU3-42.6" is a sample from a depth of 42.6 ft. in drill hole USW GU-3).

4.3.3 Measurement of Remanent Magnetization

Measurement of remanence is accomplished with a spinner magnetometer. The techniques are described by Hunt and others (1979) and in the manufacturer's manuals (Schonstedt 1975 and 1972).

4.3.4 Measurement of Susceptibility

Susceptibility is measured on a device described in Christie and Symons (1969) and calibrated as described in Rosenbaum and others (1979).

4.3.5 Alternating Field Demagnetization

Alternating field demagnetization is accomplished with either of two commercially available units according to procedures described in the manufacturer's manuals (Schonstedt 1980, and 1981). In one device the sample is stationary during the demagnetization cycle; in the other, the sample is tumbled about three orthogonal axes. The tumbling device is always used, unless the sample appears to be so delicate that the tumbling action might destroy the sample.

4.3.6 Thermal Demagnetization

Thermal demagnetization is accomplished in ovens as described by Hunt and others (1979) or in a commercial unit (Schonstedt, 1976) according to procedures described in the manufacturers manual.

4.3.7 Determination of Curie Temperature

The Curie balance and procedure for its use are described by Hunt and others (1979) and Larson and others (1975).

4.4 Alternative Methods Applicable

The methods used in this procedure tend to be straight-forward and use techniques and instruments that are specifically designed for the methods used. The two alternative methods described as follows are seen as the only deviations from the methods described above.

4.4.1 Alternate method of measuring Remanent magnetization

The most commonly used instrument for measuring magnetization of geological samples, other than the spinner magnetometer, is the cryogenic magnetometer (see Collinson, 1983, p. 268-277).

4.4.2 Oriented hand specimen collection from outcrop

If necessary, paleomagnetic samples may be collected as oriented hand specimens and cored in the laboratory (Hunt and others, 1979).

4.5 Materials/Equipment Required

The materials required consist of the host rock being studied, which is available for either insitu coring, or through core samples that are again cored for the desired test samples. The following list is comprised of the equipment items for taking the samples, for conditioning the samples, and for obtaining the magnetic data.

1. Field and Laboratory coring equipment.
2. Magnetometer (such as Schonstedt spinner magnetometer (Model DSM-1))
3. Alternating field demagnetizer (such as Schonstedt Model GSD-5)
4. Thermal demagnetizer (such as Schonstedt Model TSD-1)
5. Curie balance.
6. Magnetic and sun compasses.

4.6 Assumptions Affecting the Procedure

This procedure is an application of basic magnetic principles and is not dependent on any assumptions on the part of the investigators.

4.7 Data Information

The data collected concerns the magnetic direction and intensity of samples, the location and orientation of the samples, the sample volume and its magnetic susceptibility. The interpretation of these data and any direct use of the data is the subject of other tasks.

4.8 Limitations

In general, the use of this procedure is limited by the occurrence of weak magnetism that is below the range of the spinner magnetometer sensitivity of 10^{-3} Amp/M. Also the ability to magnetically clean the sample in an alternating field is limited to 100 mT.

5.0 CALIBRATION REQUIREMENTS

Calibration is an important part of this Technical Procedure. It is understood that all instruments, and methods where appropriate, will be calibrated according to appropriate standards prior to obtaining data that will be cited in support of the NNWSI Project.

5.1 Calibration Responsibility

The responsibility for timely conduct and maintenance of the calibrations required in this procedure lies with The Project Chief; and the performance of the calibration task in accordance with procedures as described or referenced in Section 5.2 will be done by or under the direct supervision of the Project Chief.

5.2 Calibration Procedure

Several instruments used in this procedure require calibration prior to taking data. Recalibration is required only to re-assure that the instruments are functioning properly and will be done intermittently but no less frequently than every six months as specified below for each instrument. The instruments requiring calibration are:

1. Spinner magnetometer
2. Alternating field demagnetizer
3. Thermal demagnetizer
4. Susceptometer

5.2.1 Calibration of Spinner Magnetometer

Calibration of the spinner magnetometer is accomplished by measuring a known magnetic field (generated by a DC current through a reference coil) in accordance with the manufacturer's instructions. The instrument is calibrated so that remanence directions are within 1° and intensities are within $\pm 10\%$. Calibration is to be checked every six months.

5.2.2 Calibration of Alternating Field Demagnetizer

The peak field generated by the coil of the alternating field demagnetizer is checked with a Hall-effect probe every six months. If the output deviates from the panel settings by more than 5% then the electronics are adjusted according to the manufacturer's instructions.

5.2.3 Calibration of the Thermal Demagnetizer

The temperature of the thermal demagnetizer is monitored on each run by means of a chromel-alumel thermocouple in contact with the samples. The residual magnetic field is checked every two weeks or prior to a series of experiments. If the residual magnetic field exceeds 10 mT the magnetic shield is demagnetized in accordance with the manufacturer's instructions.

5.2.4 Calibration of the Susceptometer

The susceptometer is calibrated using powders of known susceptibility described by Rosenbaum and others (1979).

5.3 Calibration Records

Calibration data will be entered in a laboratory notebook or by other organized documentation. A field notebook will be used if the test equipment is portable and used in the field. These notebooks or other documentation shall be maintained as per the Document Control Procedure (NWM-USGS-QP-01) and stored in accordance with the Records Control Procedure (NWM-USGS-QP-02). Notebooks shall contain calibration data, recalibration data, and observations made from using each instrument. Minimum data will include instrument type, instrument identification, instrument location, calibration procedure used, calibration date, calibration standard used, calibration range and accuracy, recalibration due date, responsible division subunit, and the name of the person calibrating the instrument. Calibration entries shall be signed and dated by the person performing the calibration. If laboratory or field notebooks are not used, the calibration shall be recorded on data sheets or logs and filed.

5.4 Equipment Calibration Status Labeling

As specified in NWM-USGS-QP-06, R2, all equipment used to perform this procedure must display at some readily accessible location a notation of its calibration status. To comply, a sticker will be affixed to each piece of equipment used in this procedure denoting the calibration status according to one of the following three categories:

1. Showing equipment identification, date calibrated, date recalibration is due, procedure number and calibrator.
2. Indicating the equipment identification, "OPERATOR TO CALIBRATE", and the Procedure number.
3. Showing the equipment identification and "NO CALIBRATION REQUIRED".

Appropriate stickers to accomplish this requirement will be obtained through the NNWSI-USGS Project QA office.

6.0 DATA PROCEDURES

It is acknowledged that the data obtained is largely the summary work product from this procedure. Accordingly, the following formalized procedure will be followed in documenting, accepting, and storing the data.

- 6.1 Notebooks and log books will be prepared by the Principal Investigator as necessary to record data for the project and shall include any information considered by the originator to be pertinent to the project. When data is kept in loose leaf form, each page will be numbered consecutively and chronologically. These documents will have revisions lined out, initialed, and dated and will be signed or initialed and dated by the originator on a daily basis when entries are made. Examples of the data records are included in the Attachments.
- 6.2 All data collected to provide a means of assuring the accuracy, validity, and applicability of the methods used to determine paleomagnetic and rock magnetic properties will be reviewed and cosigned by a peer knowledgeable with the objectives of this procedure in accordance with NWM-USGS-QP-01, R1 Section 12.3; and as such is acknowledged by both the investigator and the reviewer to be acceptable and meaningful data that meets appropriate quantitative and qualitative acceptance criteria.

7.0 IDENTIFICATION AND CONTROL OF SAMPLES

- 7.1 As part of the data records and documentation, all samples are identified according to a procedure that includes placing a code number on each sample with indelible ink. The code number for

surface samples includes identification of the site and a sample number. An illustration of this code is JR81-4-XX, which denotes the project chief, (JR); the year collected, (81); the site No., (4); and a consecutive sample number, (XX); respectively. The drillhole samples are identified by adding the sample depth to an abbreviation of the borehole identification. As an example, a sample taken at a depth of 42.5 ft. in borehole No. USW GU-3 is labeled "GU3-42.5".

- 7.2 The collected and identified samples shall reside in the control of the Project Chief, who shall keep the samples on file in his office or laboratory until the project is completed, at which time the Branch Chief shall determine the sample retention procedure in accordance with direction from the NNWSI project office.

8.0 MODIFICATIONS

Significant procedural changes, which are made in any field, laboratory or office methods, shall be fully documented in subsequent revisions of this Technical Detailed Procedure, and will be subject to QA, peer review, and signature approval.

- 8.1 If during the course of determining the rock and paleomagnetic properties of the given samples it is necessary to deviate from the approved procedure, defined herein, the Branch Chief shall be informed; and the procedural changes shall be documented before proceeding.
- 8.2 All procedural change documentation shall describe the modifications, give the sections of the procedure affected, and shall be dated and signed by both the Project Chief and the Branch Chief.

9.0 REFERENCES CITED

- 9.1 Christie, K. W., and D. T. A. Symons, 1969, Apparatus for measuring magnetic susceptibility and its anisotropy, Geological Survey of Canada, Paper 69-41, 10p.
- 9.2 Collinson, D. W. 1983, Methods in Rock Magnetism and Paleomagnetism, Chapman and Hall, 503p.
- 9.3 Creer, K. M. and M. Sanver, 1967, The use of the sun compass, in Methods in Paleomagnetism, D.W. Collinson, K. M. Creer and S. K. Runcorn editors, Elsevier Publishing Co., 1967, p. 11-15.
- 9.4 Doell, R. R. and A. Cox, 1967, Paleomagnetic sampling with a portable coring drill, in Methods in Paleomagnetism, D. W. Collinson, K. M. Creer and S. K. Runcorn editors, Elsevier Publishing Co., 1967, p. 21-25.
- 9.5 Hunt, G. R., G. R. Johnson, G. R. Olhoeft, D. E. Watson and K. Watson, 1979, Initial Report of the Petrophysics Laboratory, U.S. Geological Survey Circular 789, 74p.
- 9.6 Larson, E. E., R. P. Hoblitt and D. E. Watson, 1975, Gas-mixing techniques in thermomagnetic analysis, Geophysical Journal of the Royal Astronomical Society, V. 43, p. 607-620.
- 9.7 Nagata, T., 1961, Rock Magnetism, Maruzen Co. Ltd., Tokyo
- 9.8 Rosenbaum, J., E. Larson, R. Hoblitt and F. R. Fickett, 1979, A convenient standard for low-field susceptibility calibration, Review of Scientific Instruments, V. 50, p. 1027-1029.
- 9.9 Schonstedt Instrument Co., 1972, Instruction Manual for SSM-1 and SSM-1A Spinner Magnetometer.
- 9.10 Schonstedt Instrument Co., 1975, Instruction Manual for DSM Digital Spinner Magnetometer.
- 9.11 Schonstedt Instrument Co., 1976, Instruction Manual for Model TSD-1 Thermal Specimen Demagnetizer.
- 9.12 Schonstedt Instrument Co., 1980, Instruction Manual for GSD-1 AC Geophysical Specimen Demagnetizer.
- 9.13 Schonstedt Instrument Co., 1981, Preliminary Instruction Manual for GSD-5 AC Tumbling - Specimen Demagnetizer.

10.0 ATTACHMENTS

The following attachments are included with this Technical Detailed Procedure for the purpose of examples as described:

- Attachment 1. Instrument Cover Pages
- Attachment 2. Samples of Data Output
- Attachment 3. Description of Cryogenic Magnetometer
- Attachment 4. Write up on "the use of the Sun Compass"
- Attachment 5. Write up on "Paleomagnetic Sampling" with a Portable Coring Drill
- Attachment 6. Write up on Magnetic Properties

W71-USGS-GFP-06, RC
Attachment 1

SCHONSTEDT INSTRUMENT COMPANY
1775 Wiehle Avenue
Reston Virginia 22090
703-471-1050
TWX 710-833-9880

GSD-1
AC GEOPHYSICAL
SPECIMEN DEMAGNETIZER

November 13, 1980

SCHONSTEDT INSTRUMENT COMPANY

1775 Wiehle Avenue
Reston, Virginia 22070

ITS 8-900-471-1050

INSTRUCTION MANUAL

**SSM-1 and SSM-1A
SPINNER MAGNETOMETER**

SCHONSTEDT INSTRUMENT COMPANY
1775 Wiehle Avenue
Reston, Virginia 22090

PRELIMINARY
INSTRUCTION MANUAL

GSD-5
AC TUMBLING - SPECIMEN
DEMAGNETIZER

October 1981

SCHONSTEDT INSTRUMENT COMPANY
1775 Wiehle Avenue
Reston, Virginia 22090
Area Code 703 471-1050

MODEL TSD-1
THERMAL SPECIMEN
DEMAGNETIZER

STM-101
October, 1976

NW1-USGS-GPP-06, R0
Attachment #1

SCHONSTEDT INSTRUMENT COMPANY
1775 Wiehle Avenue
Reston, Virginia 22090

INSTRUCTION MANUAL

**DSM DIGITAL
SPINNER MAGNETOMETER**

May 1975

Example: Data output of measurements on spinner magnetometer
(Schonsted Model DSM-1)

SN=G3-4452.9
DN=NRM

SPIN
E1=.5770000E-3 N1=-.1277500E-2 CI=-.2370050E-5
V1=.03025000E-3 N2=-.1192500E-2 CI=-.21505213E-5
N3=-.10357500E-2 E2=.10417500E-2 CI=-.50021142E-5
N4=-.1440000E-2 V2=.1000000E-5 CI=-.2500000E-5
E3=.9010000E-3 V3=.5750000E-5 CI=-.4208940E-5
V4=.3405000E-3 E4=.0405000E-3 CI=-.24748737E-5
N=.1331137E-2 SD=.1731286E-3 NE= 70
E=.7910250E-3 SD=.1881343E-3 EV= 281
V=.2425000E-3 SD=.2071900E-3 VN= 3320
D1= 1501 I= -87 M=.10103277E-2
S
G=0900
H=0900
D3= 1070 I= 590

SN=G3-4452.9
DN=100 CE

SPIN
E1=.43925000E-3 N1=-.12682500E-2 CI=-.16007811E-5
V1=-.7530000E-3 N2=-.1251000E-2 CI=-.31457810E-5
N3=-.1505000E-2 E2=.8535000E-3 CI=-.9002540E-6
V4=-.1429500E-2 V2=-.1042500E-3 CI=-.31907636E-5
E3=.7057500E-3 V3=-.2152500E-3 CI=.22300680E-5
V4=-.4842500E-3 E4=.5212500E-3 CI=-.19202864E-5
N=-.13784375E-2 SD=.12825224E-3 NE= 95
E=.6299375E-3 SD=.16116949E-3 EV= 259
V=-.3110275E-3 SD=.22783014E-3 VN= -233
D1= 1554 I= -152 M=.15704769E-2
D2= 909 I= 462 M=.23404021E-3
D3= 1231 I= 613

SN=G3-4559.9
DN=NRM

SPIN
E1=-.4975000E-3 N1=-.4050000E-3 CI=-.23848480E-5
V1=.7035000E-3 N2=-.4212500E-3 CI=-.21213203E-5
N3=-.4032500E-3 E2=-.5425000E-3 CI=-.20310090E-5
N4=-.4035000E-3 V2=.7245000E-3 CI=.24109127E-5
E3=-.4802500E-3 V3=.7470000E-3 CI=-.10006602E-5
V4=.6915000E-3 E4=-.4997500E-3 CI=.52201362E-5
N=-.4082500E-3 SD=.75353334E-5 NE= -25
E=-.5005000E-3 SD=.21404525E-4 EV= -28
V=.7100250E-3 SD=.21143483E-4 VN= -18
D1= 2311 I= 477 M=.96786451E-3
S
G=0900
H=0900
D3= -353 I= 249

SN=G3-4559.9
DN=100 CE

SPIN
E1=-.5070000E-3 N1=-.3125000E-3 CI=-.10202804E-5
V1=.0195000E-3 N2=-.3040000E-3 CI=.18200275E-5
N3=-.3055000E-3 E2=-.5985000E-3 CI=-.25124089E-5
N4=-.3190000E-3 V2=.6292500E-3 CI=.41382363E-5
E3=-.5540000E-3 V3=.6400000E-3 CI=.12747549E-5
V4=.5987500E-3 E4=-.5882500E-3 CI=.55901099E-6
N=-.3102500E-3 SD=.59843546E-5 NE= -18
E=-.5769375E-3 SD=.17448473E-4 EV= -30
V=.6218750E-3 SD=.15193029E-4 VN= 7
D1= 2417 I= 435 M=.90323887E-3
D2= 1442 I= 381 M=.15343730E-3
D3= -429 I= 200

procedure may dissolve surface magnetic grains or carbonate cement in sandstones.

Whether random magnetometer noise is essentially being measured or a true but weak NRM can be tested by repeat measurement of samples. This will also provide information on the accuracy to be assigned to the measured direction and intensity of any weak NRM present. It may be necessary to allow for permanent residual magnetism of the sample holder, if used, by a blank measurement without the sample. Strangway and McMahon (1973) describe the successful measurement of very weakly magnetized samples of the Green river sediments (Colorado) with NRM in the range $0.5-2.0 \times 10^{-8} \text{ A m}^2 \text{ kg}^{-1}$, using the Princeton Applied Research magnetometer.

With weakly magnetized samples, it may be worth considering whether one NRM measurement using a time constant T or two measurements at $T/2$ is preferred. The total measuring time is approximately constant in each case. If the noise on the signals is proportional to $T^{-1/2}$ the fractional error in X , Y and Z is the same for each method, but the double measurement provides information on repeatability.

9.4 The cryogenic magnetometer

This type of magnetometer, which came into use in the early 1970s, depends on various effects associated with superconductivity, namely persistent currents, the Josephson weak link and flux quantization. It is also known as a SQUID magnetometer, an acronym for Superconducting Quantum Interference Device, derived from a phenomenon which is analogous to optical interference and which occurs in some superconducting circuits.

9.4.1 Operating principle

A detailed description of the complex physics involved in SQUID operation is beyond the scope of this book, and the following account is intended to clarify the basic principles of the technique. For a more detailed analysis of the operation of SQUID devices the reader is referred to papers by Deaver and Goree (1967), Gallop and Petley (1976), Goree and Fuller (1976) and Petley (1980).

The principle of SQUID operation may be understood by reference to a superconducting ring of area A which has been cooled through the critical temperature in the presence of a magnetic field B_z directed along the ring axis. If B_z changes after the superconducting state is achieved a circulating current I is set up in the ring of magnitude and sense exactly that required to cancel the change in flux $\Delta\phi = \Delta(B_z A)$ linking the ring. However, if I exceeds a critical value I_c , the critical current density in the ring is exceeded and the superconducting property suppressed. The ring becomes resistive, I decreases and the flux linking the ring increases or decreases according to the sense of

Measurement of the NRM of rocks 269

ΔB_e . The change in flux is quantized and $\Delta\phi = n\phi_0$, where n is an integer and ϕ_0 is the flux quantum. It can be shown that $\phi_0 = h/2e = 2.07 \times 10^{-15}$ Wb.

When I decreases because of loss of superconductivity, it falls below the critical value I_c and therefore the superconducting state is regained, and as long as B_e continues to change sufficiently for I to become greater than I_c the flux linkage with the ring changes, becoming constant when B_e remains constant and $I < I_c$. It can be seen that the circulating current resulting from a change ΔB_e in the external field is a measure of the field change and the sensitivity of the SQUID sensor relies on the detection of extremely small current changes.

To achieve this sensitivity the cross-section at a point in the circumference of the ring is reduced to a very small area, of the order of $1 \mu\text{m}$ across. This is the Josephson weak link or Josephson junction. A very small change in applied flux of the order ϕ_0 can now cause the critical current density in the ring to be exceeded at the junction, and the suppression of superconductivity. Suppose now that the ring is driven by a sinusoidal external field superimposed on B_e and of sufficient amplitude to cause I to exceed I_c . At each point in the cycle where I_c is exceeded and a flux quantum enters the ring the change in flux linking the ring can be detected by a voltage spike induced in a suitably placed pick-up coil. If B_e now changes, the resulting current in the ring will cause the resistive switching to occur at a different point in each cycle and alter the character of the output voltage. There is an analogy here with the operation of a fluxgate magnetometer, in which the points in a magnetizing cycle at which a high-permeability core reaches and leaves saturation is varied by a weak field which alters the core magnetization. However, there are two important differences between fluxgate and SQUID operation. The fluxgate ceases to operate if the external field saturates the core, whereas when I_c is exceeded in the SQUID flux enters the ring and the system resets itself to a lower current value. Also, a fluxgate measures absolute field values but the SQUID output is a measure of the change of field in the ring from the field present when it became superconducting.

Current SQUID magnetometers employ a drive frequency of 20–30 MHz with circulating currents of the order of $1 \mu\text{A}$ corresponding to a change of one flux quantum in the detector. For reasons associated with thermal noise the detector must be very small and possess a small self-inductance ($< 1 \mu\text{H}$) and there are two common configurations. One is a quartz cylinder ($\sim 2 \text{ mm}$ in diameter) on the curved surface of which a thin layer of superconductor is deposited. A longitudinal slot is cut in the layer except for a very narrow ($\sim 0.1 \mu\text{m}$) bridge (Dayem bridge) at the centre, which forms the weak link. The drive coil, from which the output signal is also obtained, is wound on top of the superconducting layer. An alternative form of detector is a ring in which the weak link is formed at the point of a fine screw bearing on a flat surface.

For an estimate of SQUID sensitivity consider a cylindrical detector of diameter 2 mm. A field change of $\sim 7 \times 10^{-10}$ T along the cylinder axis

iii

;

ic

ne

;

n.

. or

of

corresponds to a change of one flux quantum. Since it is possible to detect a change of $10^{-3} \phi_0$, a field of 7×10^{-13} T can be detected by the sensor.

In principle the weak link sensor can be used directly for magnetic field measurements but it is advantageous on several counts, particularly for NRM measurements, to detect the field initially by means of a superconducting pick-up coil. This is linked by superconducting leads to a field coil tightly coupled to the SQUID detector. This system acts as a form of zero-frequency field transformer, based on the condition that the flux linkages within the circuit must remain constant. Thus, for a given field more flux is linked with the sensor because of the large pick-up coil area relative to the effective SQUID area, and substantial field amplification by a factor of 20-50 can be obtained. The use of pick-up coils is also a much more satisfactory (electromagnetically) and convenient way of detecting the field of a rock sample than placing it near the sensor.

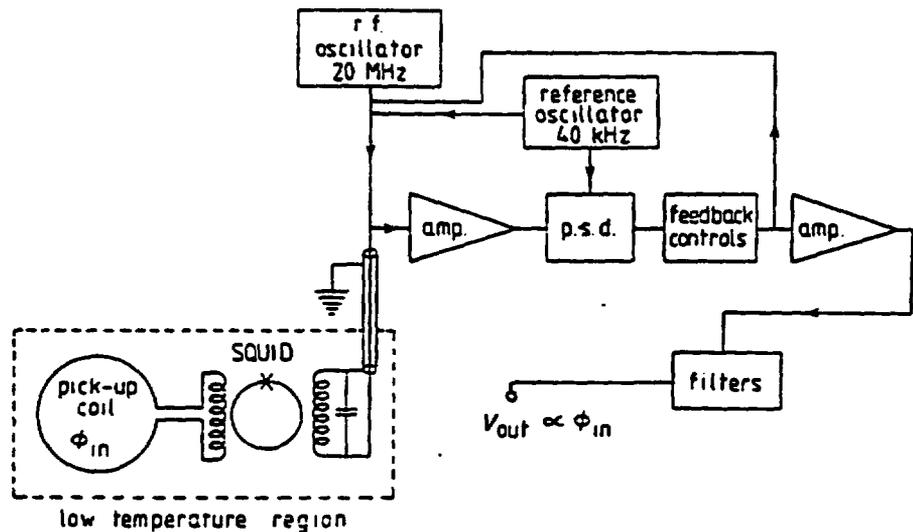


Fig. 9.23 Block diagram of CCL cryogenic magnetometer. (Courtesy of Cryogenic Consultants Ltd, London)

The output obtained from the SQUID is non-linear with the applied field and it is usual to apply feedback to the sensor via a coil, the current or voltage in which is then proportional to the applied field. A block diagram of a cryogenic magnetometer is shown in Fig. 9.23.

9.4.2 The SCT and CCL cryogenic magnetometers

At the time of writing there are two commercially built SQUID rock magnetometers on the market. The Superconducting Technology instrument

Measurement of the NRM of rocks 271

(USA) has been available for about 12 years and more recently Cryogenic Consultants Ltd (London) have entered the market. The construction of both instruments is similar and they only differ in some details: a diagram of the CCL instrument is shown in Fig. 9.24. The CCL instrument is pre-cooled with liquid nitrogen, contained in the upper tank (~ 20 l capacity), which cools the helium chamber by means of the radiation shield and assists in reducing helium loss during operation. Both the nitrogen and helium chambers are surrounded by vacuum spaces which can be pumped out prior to cooling. The pick-up coils and SQUID detectors are shielded from external magnetic fields by a niobium superconducting shield and also, in the CCL instrument, by a magnetic shield of Mumetal. The sample access tube is 3.5 cm in diameter and is normally at a temperature above 0°C. Liquid helium is transferred from a storage Dewar to the magnetometer chamber by reducing the pressure in the latter. About 5 l are required to cool the chamber before liquid helium begins to collect and the chamber capacity is ~ 24 l. Helium gas is exhausted from the top of the chamber and passes to the atmosphere via a flowmeter, by means of which the boil-off rate may be monitored. In the author's magnetometer it is normally 0.2-0.5 l/min of helium gas, corresponding to about 1.2 l of liquid helium per day.

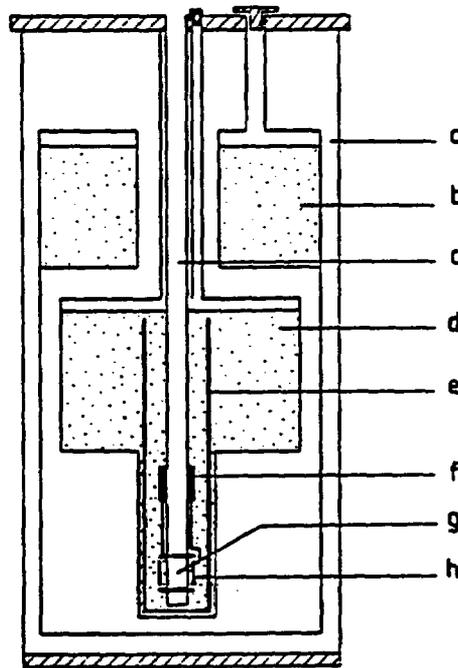


Fig. 9.24 CCL two-axis cryogenic magnetometer. a, vacuum space and super-insulation; b, liquid nitrogen; c, sample access tube; d, liquid helium; e, mumetal and superconducting shields; f, SQUID units; g, measurement position; h, pick-up coils.

still
ie
tic
the
o
ie
:k
n,
or
of

272 *Methods in Rock Magnetism and Palaeomagnetism*

The construction of the SCT magnetometer is simpler in one respect in that no liquid nitrogen is used, the helium chamber being enclosed in 'super-insulation'. There is some sacrifice in helium consumption, and the boil-off rate is around 2-3 l/day. If it is economically justified some users of cryogenic magnetometers collect the helium gas, compress it into cylinders and return it to the supplier. It may also be possible to use a continuous refrigeration system, available with both magnetometers, although these are expensive and have sometimes been found to be a source of noise in the SQUID output.

The standard SCT instrument has an access 6.3 cm in diameter, with a helium chamber capacity of 30 l. A single superconducting shield surrounds the SQUIDS and pick-up coils.

Both magnetometers can be provided with pick-up coils for measurement of NRM along one sample axis, or for simultaneous measurement along two or three mutually perpendicular axes. The common configuration is a pair of coils for each axis, one of each pair on either side of the access tube to detect the radial components of NRM and a pair (four in the CCL instrument) coaxial with the tube and symmetrically placed about the measuring position for the axial NRM component. Each coil pair is connected to its own SQUID detector, forming the field amplification system already described. The pick-up coils, leads and SQUID coil are, of course, all superconducting. The output signal from each SQUID is proportional to the flux change produced by the appropriate NRM component and is independent of the rate of change of flux, i.e. of the rate at which the sample is inserted into the pick-up coils. However, if the rate of change of flux is too fast there may be loss of lock in the feedback loop. In practice this maximum allowable 'slew rate' is not normally restrictive, and loss of lock is only likely to occur when strongly magnetized samples are rapidly inserted into the measuring space.

The sample is lowered to the measuring position and, if necessary, oriented to different angular positions there by a sample insertion system mounted on top of the magnetometer. This takes the general form of a carriage moving on vertical guides of sufficient height so that the sample holder, fixed at the lower end of a vertical stem attached to the carriage at its upper end, can be raised above the magnetometer top plate and lowered to the measuring position. Provision for rotating the sample to different (orthogonal) azimuths about the vertical axis will also usually be required in one- or two-axis instruments, and also a 'background' measuring position. The latter is a position where the sample magnetization does not couple significantly with the pick-up coils and where readings of the 'zero-level' SQUID outputs can be recorded immediately before and after measurement of the sample.

Under ideal conditions of very low external noise the noise level of the two cryogenic magnetometers is stated to be $(5-10) \times 10^{-12}$ A m² total moment, using an averaging time of ~ 1 s. For a standard cylindrical sample 2.5 cm in diameter and 2.2 cm high, this noise level is equivalent to a specific magnetization of $\sim (2-4) \times 10^{-10}$ A m² kg⁻¹. However, as in the case with all

Measurement of the NRM of rocks 273

rock magnetometers, the useful limit of performance depends on the level of external sources of both random and systematic noise. Depending on the measurement procedure used, total measurement time is ~1-2 minutes per sample.

Probably the most common cause of random noise is fluctuations in the ambient laboratory magnetic field. Although the superconducting and Mumetal shields provide a high degree of protection against field variations, the exceptionally sensitive SQUID detector may still respond to residual variations. These can be further decreased by operating the magnetometer inside a single- or double-walled ferromagnetic shield fitting closely round it, or in a shielded room. Other potential sources of noise are mechanical vibration, r.f. interference, and temperature variations in the liquid helium. The latter may occur if there are pressure variations in the helium chamber, for example from wind blowing across the opening of the exhaust vent, or pressure variations in a gas collection system. A possible source of vibration is the sample touching the side of the access tube during insertion and withdrawal. It may be helpful to fix a guide to the stem above the holder to maintain the holder in a central position.

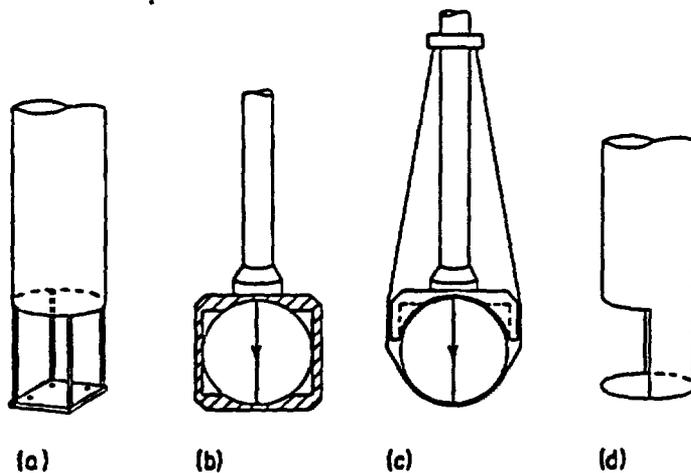


Fig. 9.25 Some examples of sample holders for the cryogenic magnetometer: (a) and (d) are mounted on and cut out of Mylar tube respectively; (b) is as narrow as possible consistent with sample location; in (c) the sample is held in place with an elastic band; (d) is only suitable where the sample is measured with its axis vertical.

If the ultimate sensitivity of the magnetometer is approached sources of systematic and random noise which are otherwise usually negligible must be eliminated. Among the latter are magnetization of the sample holder and the residual magnetic field at the measuring position. The holder should be of minimum size and mass, and among suitable materials are Perspex (lucite),

o
ce
rd
=
ly still

line
netic

in the
it to

the

ll
ock
sm.

its or
is of
f

274 *Methods in Rock Magnetism and Palaeomagnetism*

wood, glass, quartz or nylon. Frequent washing or treatment in an ultrasonic bath is desirable and, if necessary, a.f. demagnetization of intrinsic ferromagnetic contamination. Some examples of holders for supporting a cylindrical sample with its axis vertical or horizontal are shown in Fig. 9.25.

Although in principle the effect of a residual field at the measuring position and resulting induced magnetization can be meaned out by measuring the samples in appropriate orientations, a fewer number of sample manipulations and saving of time is achieved if any induced magnetization is negligibly small. As an example, if a magnetization of $1 \times 10^{-8} \text{ A m}^2 \text{ kg}^{-1}$ is required to be measured, with reasonable accuracy, the induced component should be $< 1 \times 10^{-9} \text{ A m}^2$. A weakly magnetized sediment may have a mass susceptibility of $\sim 1 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$, resulting in the above induced magnetization in a field of $\sim 100 \text{ nT}$. This field is probably a useful maximum value to aim for the measuring position. It should not be forgotten that many rock-forming minerals have a significant paramagnetic or diamagnetic susceptibility of $\sim 10^{-8} \text{ m}^3 \text{ kg}^{-1}$ or more (Table 2.1) and that the holder material may also contribute in this context. However, the much smaller mass of the latter relative to the sample ensures a smaller contribution to induced magnetization from this source.

The method of achieving a low residual field in the measuring space depends on the shielding provided. The SCT magnetometer has a superconducting shield only, and thus traps the field present when cooled through the critical temperature. A suitably low field can be obtained in a Helmholtz coil system. In the currently available CCL magnetometer there is a Mumetal shield nested between two superconducting shields. This system has some disadvantages, in that it may not be possible to completely demagnetize the Mumetal shield. Any remanent magnetization remaining varies with temperature and results in a substantial change in the residual field during pre-cooling with liquid nitrogen, necessitating further demagnetization. The axial residual field is usually the stronger, and demagnetization can be carried out by means of a coil placed around the barrel of the instrument. The author has also had some success with magnetizing the shield in the appropriate direction to adjust the remanence during cooling, using either a solenoid inserted in the access tube at the measuring position or the external coil.

Measuring procedure with the cryogenic magnetometer depends on the number of axes along which NRM can be simultaneously measured, the degree to which the pick-up coils can accommodate inhomogeneity of NRM, and whether it is considered desirable to mean out induced magnetization. In both magnetometers the response of the pick-up coils is uniform to about 2% over the volume of a standard sample, but experience suggest that it is advantageous to use a procedure whereby at least four readings each of the X, Y and Z components are obtained, particularly when within a factor of 10 of the noise level of the instrument.

There are advantages in operating the magnetometer in a low magnetic field

enviro
This e
shieldi
and re

9.4.3

A SQI
sampi
of whi
1.0 cm
introd
cavity
contri
signal
comp
coils.
magn:
positi
modifi
signal

The
Thelli
heatir
with
suppli
a dot
Howe
below
capac
to be

Th
~1.0
Eq

Card:
syster
silica
positi
vertic
the cr
the h
vertic
alterr
pend

Measurement of the NRM of rocks 275

environment, using a Helmholtz or other coil system or a small shielded room. This eliminates the enhanced magnetic field at the mouth of the internal shielding, and also provides a low ambient field at the sample during loading and re-orientation.

9.4.3 Other cryogenic magnetometers

A SQUID magnetometer designed for measurement of small archaeological samples (typical dimension ~ 0.3 cm) is described by Walton (1977), a diagram of which is shown in Fig. 9.26. The measuring position is in a re-entrant cavity 1.0 cm in diameter on the underside of the helium chamber and the sample is introduced from below. The pick-up coils are placed close to the walls of the cavity and consist of a pair of axial and radial coils connected in series to form a continuous circuit. When the sample is inserted into the cavity the output signal is proportional to the sum of the vertical component of NRM and the component of the horizontal NRM perpendicular to the horizontal pick-up coils. If the sample is then rotated about the vertical axis the phase and magnitude of the horizontal component can be determined from the angular positions of the sample for minimum and maximum output. In a later modification the sample is rotated continuously at ~ 3 Hz and the resulting signal computer-analysed.

The magnetometer is mainly used for palaeointensity determinations by the Thellier method. A small furnace was originally placed in the cavity for in-situ heating of the sample, using alternating current at 33 kHz to avoid interference with the SQUID. A 150-turn coil wound on the outside of the cryostat supplied the (vertical) applied field and the whole instrument is operated inside a double-walled Mumetal shield, maintaining the internal field at $\sim 1 \mu\text{T}$. However, better results were obtained with the furnace placed just outside and below the cavity, along with vertical and horizontal applied field coils. The capacity of the liquid helium chamber is 7 l, which enables the magnetometer to be used for about two weeks.

The noise level in the magnetometer is equivalent to a total moment of $\sim 1.0 \times 10^{-4} \text{ A m}^2$, which in a 3 mm sample is about $4 \times 10^{-8} \text{ A m}^2 \text{ kg}^{-1}$.

Equipment designed by J. Shaw and J. Rogers at University College, Cardiff, Wales consist of an integrated magnetometer and magnetic cleaning system (thermal and alternating field). At the centre of the system is a vertical silica access tube, at the lower end of which is the pick-up coil and measuring position. The pick-up coil is a single coil with its axis inclined at 45° to the vertical. The sample is continuously rotated at 33.3 Hz about a vertical axis at the coil centre and the SQUID output consists of an alternating signal due to the horizontal NRM component superimposed on a steady signal due to the vertical NRM component (Fig. 9.27). The amplitude and phase of the alternating signal determines the components of the magnetization perpendicular to the spin axis.

THE USE OF THE SUN COMPASS

K.M. CREER AND M. SANVER

INTRODUCTION

It is necessary to use a sun compass to orientate rock samples from formations which are strongly magnetized. This is because the magnetism of such rock formations, e.g., strongly magnetized lavas, ore bodies, etc., appreciably distorts the local geomagnetic field so that a magnetic compass no longer points in the direction given by isogonic charts.

DESCRIPTION

A sun compass consists of a square flat plate to which a thin straight rod is fixed accurately perpendicular. Azimuthal angles are marked, preferably in a counter-clockwise direction, on the flat plate concentric with the base of the rod. Two spirit levels are fixed to the plate so that it can be set horizontally. The sun compass should be set against the rock face with its "0°" mark pointing in the direction whose bearing is required, i.e., with the "90°" mark nearest the rock face. The plate is held so that it is horizontal and the azimuth of the shadow cast by the sun relative to the unknown direction is read. The time must be recorded accurately. The azimuth of the shadow relative to geographic North may be found as described below.

CALCULATION OF THE SUN'S AZIMUTH

The direction of the sun, relative to the horizontal plane and geographic North at a site, may be calculated from two angles which may be found by consulting the *Air Almanac*. These are the angle between the sun's direction and the equatorial plane and the angle between the meridians containing the site and the sun. The former varies appreciably from day to day throughout the year and is called the sun's declination (Fig.1). Although the declination is listed in the *Air Almanac* at 10-min intervals for each day of the year, it does not vary significantly for our purpose from hour to hour. It varies from 23°30' N in June to 23°30' S in December. The second angle is called the local hour angle, H (Fig.2). In the *Air Almanac* the Greenwich hour angle, G , is listed for each day of the year at 10-min intervals. For our purpose the variation from day to day is not significant but the variation during the day is and this is why the local time must be recorded. The local time should be converted to Greenwich time and the Greenwich hour angle read off from the tables. The local hour angle is given by adding the longitude (°E of Greenwich) to the Greenwich hour angle.

TABLE I

ALLOTMENT OF SIGNS OF L , D , AND H

Quantity	Signs	
Latitude (L)	North, -ve	South, -ve
Declination (D)	North, -ve	South, -ve
Local hour angle (H)	$< 180^\circ$, -ve	$> 180^\circ$, use $360^\circ - H$, -ve

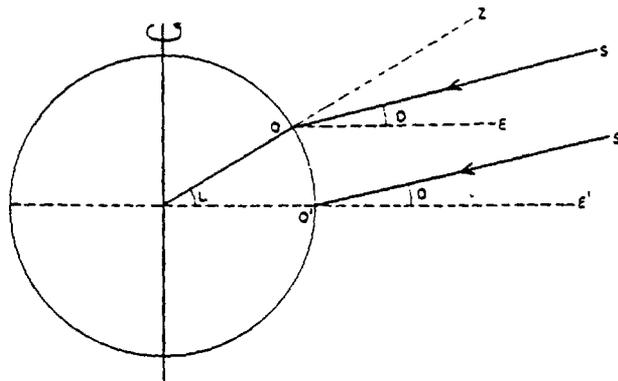


Fig.1. Diagram illustrating the declination of the sun. $O'E'$ = equatorial plane; $O'S'$, OS = direction of the sun; OZ = vertical at O . (All above lie in the plane of the paper.) L = latitude of site; D = declination of the sun. The local hour angle in this figure is zero.

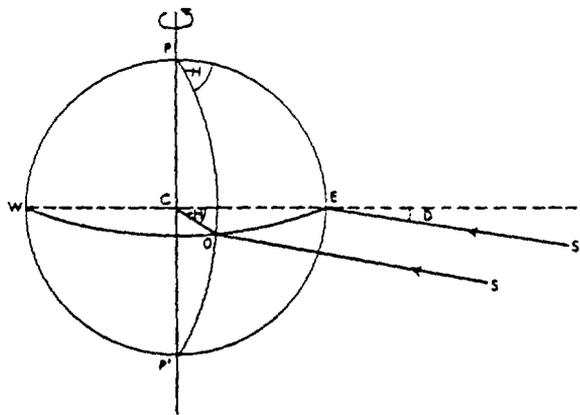


Fig.2. Diagram illustrating the local hour angle. ES' , OS = directions of the sun; EOW is the equator; PEP' = meridian plane containing the sun; POP' = meridian of site O ; H = local hour angle (angle between planes PEP' and POP' , measured in an easterly direction), H is independent of latitude L for all sites of the same meridian.

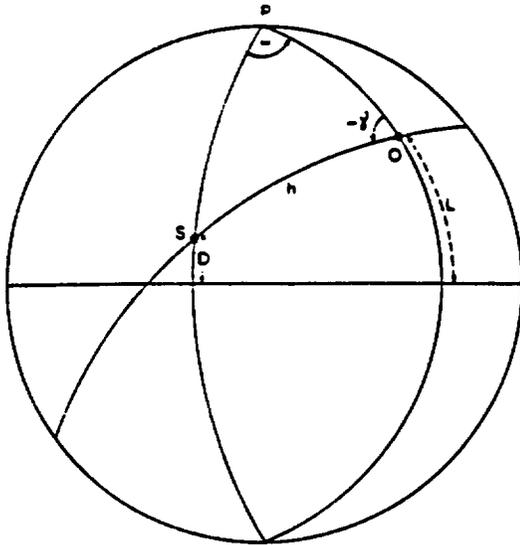


Fig.3. Relationship of L , D , H , γ and h . For explanation see text.

The azimuth, γ , of the sun may be obtained by solving the spherical triangle POS of Fig.3. We first calculate h from:

$$\cosh = \sin L \sin D + \cos L \cos D \cos H \quad (1)$$

We may then obtain γ using either the sine rule:

$$\sin \gamma = -\cos D \sin H / \sin h \quad (2)$$

or the cosine rule:

$$\cos \gamma = (\sin D - \sin L \cosh) / \cos L \sin h \quad (3)$$

Alternatively, dividing eq.2 by eq.3 and using eq.1 to eliminate \cosh , we find:

$$\tan \gamma = -\sin H / (\cos L \tan D - \sin L \cos H) \quad (4)$$

The quadrant in which γ lies depends upon the signs of H , L and D and may be deduced from Table I and II. An alternative method for obtaining γ , using sight reduction tables, is given by FRASER (1963).

As examples, Γ , the direction of the sun's shadow has been calculated for a number of different latitudes for declination 20.5°N (23 May or 21 July). The curves relating Γ with the time of day are plotted (Fig.4) for times between sunrise and sunset. Note that the sun is not exactly due north (or due south) at noon but that all the curves pass through the abscissa $\Gamma = 0$ or 180° at the same time of day (approx. 6 min after noon on these 2 days) whatever the latitude.

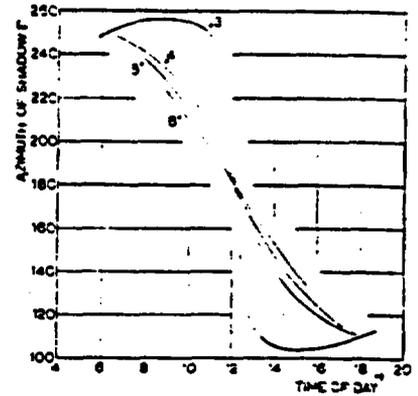
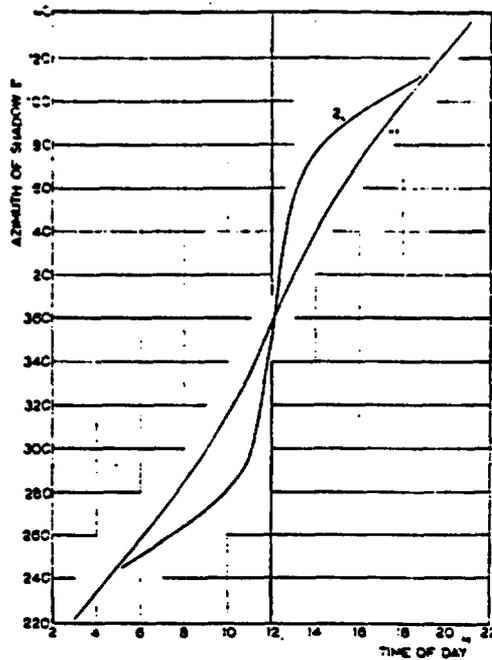


Fig.4. The direction of the sun's shadow, Γ , measured from geographic north between sunrise and sunset. All the curves are for $D = 20.5^\circ\text{N}$, but the latitudes, L , vary as follows: curve (1) 60°N , (2) 30°N , (3) 15°N , (4) 15°S , (5) 30°S and (6) 60°S .

TABLE II

QUADRANT OF AZIMUTH OF SHADOW

Signs of numerator	Eq. 4 denominator	Azimuth of shadow
-	-	Γ
-	+	$180 - \Gamma$
+	+	$180 - \Gamma$
+	-	$360 - \Gamma$

CALCULATION OF BEARING OF UNKNOWN DIRECTION

In the field

(1) Place the sun compass against the orientation arrow on the rock surface as shown in Fig.5. Ensure that the scale is level.

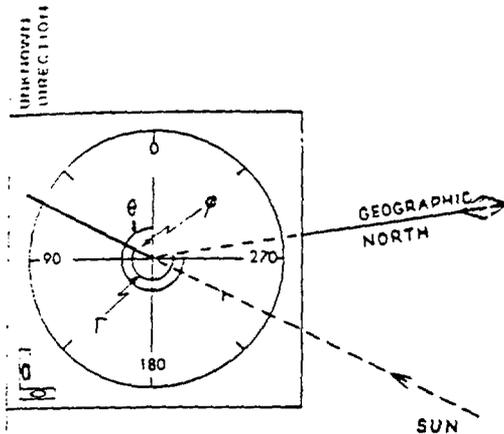


Fig.5. Calculation of unknown bearing. θ = bearing of unknown direction; Γ = azimuth of shadow; φ = angle between unknown direction and shadow; $\theta = \Gamma \div \varphi$.

(2) Record the angle φ between the shadow of the vertical rod and the azimuth zero, measured in anti-clockwise sense.

(3) Record the local time, and the date.

In the laboratory

(1) Look up the latitude and longitude of the site.

(2) Convert the local time to G.M.T.

(3) In the *Air Almanac* look up the Greenwich hour angle G and the declination D of the sun.

(4) Obtain the local hour angle H by adding the longitude °E of Greenwich to G .

(5) Calculate γ using eq.4 using the sign convention for D , L and H given in Table I.

(6) Use Table II to determine quadrant of Γ , the direction of the sun's shadow ($\Gamma = \gamma \div 180^\circ$: this has been taken into account in the derivation of Table II).

(7) The bearing θ , of the orientation arrow is given by:

$$\theta = \Gamma \div \varphi \quad (5)$$

REFERENCES

Air Almanac, published for four-monthly intervals by H.M. Stationery Office, London, and U.S. Naval Observatory, Washington.

FRASER, D. C., 1963. Sun-chart-compass corrections for reconnaissance mapping and geophysical prospecting in areas of magnetic disturbance. *Econ. Geol.*, 58: 131-137.

PALAEOMAGNETIC SAMPLING WITH A PORTABLE CORING DRILL

RICHARD R. DOELL AND ALLAN COX

INTRODUCTION

This report presents a brief description of the equipment used by the Rock Magnetism Laboratory of the U.S. Geological Survey. Much of the material presented here is included in DOELL and COX (1965). Publication in present form is authorized by the Director, U.S. Geological Survey.

DESCRIPTION OF CORING DRILL

The coring unit consists of (1) a core barrel, (2) a transmission unit with coolant fittings, (3) a power unit, (4) a coolant hose and pressure tank, and (5) an optional guide frame. The equipment is shown on display in Fig.1 and in operation with the guide frame in Fig.2.

The core barrel is a commercial sintered-diamond type manufactured for drilling holes in masonry. The standard heavy-duty drill which we employ produces a core 2.49



Fig.1. The coring unit.



Fig. 2. The coring unit with guide frame in operation.

cm nominal diameter; we have found that a core-barrel length of 20-25 cm is convenient. The threaded coupling which connects the core barrel to the transmission shaft is welded to the barrel before final machining to ensure proper alignment with the drive shaft.

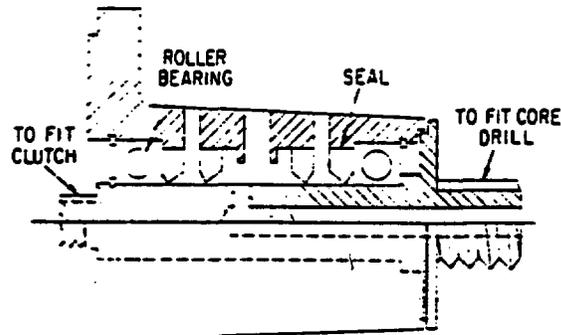


Fig. 3. The transmission unit.

ND A. COX

SAMPLING WITH A PORTABLE CORING DRILL

23

The transmission unit consists of an aluminum housing which contains the drive-shaft bearings and coolant seals and is machined to fit directly to the power unit (Fig.3). The motor clutch-plate is fitted directly to one end of the partly hollow stainless-steel drive shaft, and the core barrel is attached at the other end. The drive-shaft bearings are of the sealed roller type and are fitted at the extremities of the housing. The first set of coolant seals is fitted inside the bearings, and these are followed by grease reservoirs. The second set of seals is fitted to the inside of the grease reservoirs. The drilling coolant is introduced between these two inner seals and passes into the hollow shaft through radial holes. The double seals and grease reservoirs, which are filled through normal automotive-type grease nipples, ensure that the coolant does not enter the roller bearings; the latter are lubricated for their normal life at the factory.

The power unit we employ is a commercial single-cylinder two-cycle gasoline motor normally used to power a lumbering saw (McCullough model 35A). It develops approximately 2 h.p. at about 3,000-4,000 r.p.m., the normal drilling speed. The motor is fitted with a diaphragm-type carburetor, which allows it to run in any position, and an automatic centrifugal-type clutch that engages the plate fitted to the transmission shaft. The motor, transmission, and core barrel weigh 9 kg.

The coolant is supplied to the transmission unit through a shut-off valve and 6.4 mm inside-diameter plastic hose fitted to a commercial pressure-type garden insecticide sprayer with quick release couplings. The tank and tube shown in Fig.1 weigh 4 kg net, and will carry 9 l of coolant. Salt water and fresh water have been used for coolant, care being taken in the case of the salt water to see that it did not remain in the equipment after use. Coolant requirements vary widely depending upon rock type; however, an experienced operator requires no more than 1 l of coolant per core drilled in basalt, limestone, or similar rocks.

USE OF THE DRILL

After a little experience most workers find that it is not too difficult to drill cores 10-20 cm length in soft rocks (basalt, partly welded tuffs, siltstones, fine sandstones, or limestones) without the use of a guide. In harder rocks (quartzites, cherts, dense volcanic glasses, gneisses, or gneisses) it is generally simpler to use a guide to support and steady the drill during the longer drilling time required. Our guide is attached to the outcrop with an expansion bolt that fits a short hole drilled with the core drill for this purpose (see Fig.2). The other end of the guide is supported by two adjustable legs.

After the drill is removed, and before the core is broken from the outcrop, it must be oriented in its in situ position. For this purpose we employ a slotted brass tube which may be slipped over the drilled core and upon which is mounted an inclinometer and small open blade transit (Fig.1). These are so arranged that when the inclinometer plate is vertical, the slot in the tube lies vertically above the core axis. The inclinometer measures the inclination of the core axis below or above the horizontal, and the transit, along with other surveying aids, may be used to measure the geographic azimuth of the horizontal direction that is at right angles to the core axis and directed to the right as one views the core from the outcrop surface. A copper or brass wire is then inserted into the slot, leaving

venient.
welded
shaft.



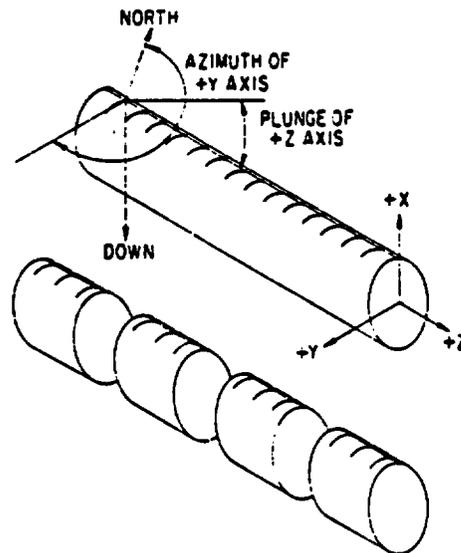


Fig.4. Core and laboratory specimens.

a mark on the uppermost part of the cylindrical surface of the core. The core may then be separated from the outcrop by inserting a wedge between it and the parent rock. If the rock is not fractured, the stress distribution during this operation ensures that the core breaks free of the parent rock at the very bottom of the cut. The core may then be removed and a diamond scribe used to make the orientation mark permanent, as well as to identify the "top" of the core. If short marks are scribed or marked from the orientation line in the direction of the geographic azimuth (as defined above), then each segment later cut from the core to make a laboratory specimen will contain a complete orientation record. A core, and laboratory specimens cut from it, is depicted in Fig.4.

DISCUSSION

The major advantage of using a portable core drill over sampling and orienting small joint blocks is that any desired portion of an outcrop may be sampled. Thus the entire sampling program may be designed around the availability of fresh rock and the desired sample spacing; it is not limited to the availability of removable joint blocks.

Accuracy in assigning orientation is uniform and of the same precision that can be obtained in placing specimens in the measuring apparatus. Without special orienting devices this precision is usually better than can be obtained by orienting "flat" faces or placing other marks on joint blocks using a geologist's compass.

There is no chance to err or lose accuracy in transcribing orientation marks from field samples to laboratory specimens, since each specimen to be cut from the core is given a complete orientation record at the time it is collected. Laboratory specimen preparation is reduced to two passes with any diamond saw blade (one pass suffices if

SAMPLING WITH A PORTABLE CORING DRILL

25

the saw is equipped with two blades spaced at the desired specimen length). On the average, each core (2.5 cm diameter by 15 cm long) weighs about 200 g. or 5 cores/kg; on the other hand, a single joint block sample of average size (say 10 cm on an edge) weighs about 2.5 kg. If many samples are desired, as is usual in modern palaeomagnetic studies, then a simple calculation of the weights involved will point out the efficiency of the in situ coring method of sample collection.

REFERENCE

DWELL, R. R. and COX, A., 1965. Measurement of the remanent magnetization of igneous rocks. *U.S. Geol. Surv., Bull.*, 1203-A: 1-32.



- pure ice I_h single crystals--I, Polarization of spectra of ice I_h: Jour. Chem. Physics, v. 54, p. 134-144.
- Wagner, K. W., 1913, Erklärung der dielectricischen--Nachwirkungen auf grund maxwellscher vorstellungen: Archiv. Electrotech., v. 2, p. 371.
- Wait, J. R., 1959, ed., Overvoltage research and geophysical applications: London, Pergamon Press, 158 p.
- Ward, S. H., 1967, Electromagnetic theory for geophysical applications: Mining Geophysics, v. 2, p. 10-196.
- Ward, S. H., and Fraser, D. C., 1967, Conduction of electricity in rocks: Mining Geophysics, v. 2, p. 197-223.
- Wooten, M. J., 1973, The conductance of electrolyte solutions, Chapter 3 of Electrochemistry: London, The Chemical Society, p. 20-40.
- Wyllie, G., 1972, Dielectric relaxation and molecular correlation, Chapter 1 of Dielectric and related molecular processes: London, The Chemical Society, p. 21-63.

MAGNETIC PROPERTIES

By Don Watson

INTRODUCTION

Paleomagnetism

Research in the field of paleomagnetism began around the turn of the century, with much of the effort being devoted to determining the Earth's main magnetic field. Because direct observations of the geomagnetic field extend back only four centuries, paleomagnetism affords the only opportunity to lengthen this record and does so by a factor of 10^7 . As a result of paleomagnetic research, a great deal of information has been obtained relating to the theories of the sources of the geomagnetic field, polar wandering and continental drift, field reversals, dating of rocks, and tectonics.

All rocks exhibit some magnetic properties owing to the presence of various iron compounds that make up only a few percent of the rock as accessory minerals. These iron compounds have acquired magnetization which is termed fossil magnetism or NRM (natural remanent magnetization). The mechanism by which the NRM was acquired depends on the methods of formation and the subsequent history of the rocks. Magnetization acquired by cooling, in the presence of a magnetic field, from high temperatures through the curie points of the magnetic minerals (as in the formation of igneous rocks) is called TRM (thermoremanent magnetization). If the magnetization is acquired by chemical action at low temperatures as in red beds, then it is termed CRM (chemical remanent magnetization). The alinement of magnetic particles during deposi-

tion of sedimentary materials is called DRM (detrital remanent magnetization). The above-mentioned components are considered the "primary magnetization" and, by definition, are supposed to reflect the direction of the geomagnetic field at the time of formation or shortly thereafter. Any other subsequent components added by a number of processes such as viscous decay, lightning discharge, chemical alteration, or thermal overprinting are referred to as "secondary magnetization." A major task in paleomagnetic investigations is to identify and eliminate these secondary components, where possible, without destroying the desired primary components.

Archaeomagnetism

Ancient pottery, bricks from kilns, and fireplaces whose last date of firing can be determined from carbon-14 techniques exhibit a thermoremanent magnetization. The study, using these materials, of the variation of declination, inclination, and intensity of the geomagnetic field is referred to as archaeomagnetism. It differs from paleomagnetism only because it makes use of manmade materials rather than rocks. Researchers who study such materials have begun to put together prehistoric secular-change curves of direction and intensity of the Earth's field for certain localities where data can be obtained that extend over a sufficiently long period of time. The most important results of this work are that a better understanding has developed as to the nature of long-term (about 10,000 years) secular variations, and this information is now being used to date archaeological material when carbon-14 determinations are impossible.

Extraterrestrial magnetism

Remanent magnetization has been found to occur in both meteorite and lunar materials. A large volume of magnetic-property measurements has been accumulated for returned lunar samples (Banerjee and Hargraves, 1971; Stacey and others, 1961; Herndon and others, 1975; Watson and others, 1975). Studies of these samples have aided in (1) modeling the interior of the moon and its evolution, (2) determining the history and formation of the lunar regolith, and (3) increasing our understanding of the nature of extraterrestrial iron minerals.

Magnetic-property investigations of meteorites have provided additional clues as to the origins of meteorites and the formation of the solar system. Carbonaceous chondrites are considered to be among the most primitive materials in the solar system. The remanent magnetization found in these rocks indicates the presence of strong magnetic fields early in the history of the solar system, even before planetary formation.

THE PRINCIPLES OF ROCK MAGNETISM

Remanent and induced magnetism

The magnetization of any material is generally made up of two components: the "remanent magnetization," which is that part remaining after removal of an applied field such as the Earth's, and the "induced magnetization," which is that part induced by an applied field but which disappears after removal of the field. (See figure 20.) In rocks, the total magnetization J is made up of the vector sum of the remanence J_n and the induced magnetization J_i , where

$$J = J_i + J_n \quad (1)$$

The induced magnetization J_i is proportional to the applied field H ; that is,

$$J_i = \chi H \quad (2)$$

where χ is the constant of proportionality called the "magnetic susceptibility." Most paleomagnetic investigations do not routinely involve susceptibility measurements; and, therefore, care is taken to shield the rocks from external magnetic fields during remanence measurements. (See section entitled "Measurement of Remanence.") On the other hand, aeromagnetic applications usually require measurements of susceptibility and, therefore, these measurement techniques will also be discussed.

Ferromagnetism, antiferromagnetism, and ferrimagnetism

Substances such as iron, nickel, and cobalt exhibit strong magnetic effects known as ferromagnetism. These elements contain unpaired electrons that are magnetically coupled between neighboring atoms. This interaction results in a strong spontaneous magnetization that causes the alignment to be retained after removal of the external applied field. As the temperature increases, thermal agitation may destroy this alignment process. This occurs at a critical temperature known as the "Curie temperature."

Some substances are characterized by a subdivision into two sublattices (A and B), in which the atomic moments within each are aligned but antiparallel to one another. The result is no net magnetic moment, and this phenomenon is known as antiferromagnetism (fig. 21). If the atomic moments of the A and B sublattices are unequal, then there is a weak, net spontaneous magnetization known as ferrimagnetism. Finally, if the atomic moments in the two sublattices are not exactly antiparallel and a weak spontaneous magnetization results (fig. 21), then the substance is said to be a canted antiferromagnetic.

Diamagnetism, paramagnetism, and superparamagnetism

Two types of magnetization are diamagnetism and paramagnetism. In its path around the nu-

cleus, an electron creates a dipole moment called the orbital magnetic moment. Also, the electron spinning about its own axis creates a spin magnetic moment. The sum of the orbital and spin moments results in the magnetic dipole moment of an atom, with most atomic moments being zero. When atoms or molecules having zero moments are placed in a magnetic field, they couple to precess about the magnetic field. This orbital precession causes a magnetic moment to be induced in each atom in the direction opposite to the applied field. This is referred to as diamagnetism. The susceptibility is negative (fig. 22A).

In an atom having a resultant magnetic moment, the application of a magnetic field aligns these moments in the direction of the field. Substances having this effect are called paramagnetics with positive susceptibility (fig. 22B).

Very fine particles, less than single domain size ($<0.01 \mu\text{m}$), have very short relaxation times (equation 4), even at room temperature. These particles are referred to as being superparamagnetic; that is, they behave paramagnetically but with intensities similar to those of ferromagnetic materials. Though the individual particles have ferromagnetic-like intensities, they rapidly change directions with an applied field and, when the field is removed, cannot maintain any remanence. Relaxation time is dependent on both volume and temperature and is much less than 1 sec for superparamagnetic particles. Superparamagnetism is not normally observed in terrestrial rocks, but can influence magnetic-property measurements of lunar and meteoritic materials owing to the presence of extremely fine grained iron.

Magnetic minerals in rocks

The minerals that are most frequently found to be responsible for the magnetic properties of rocks are within the ternary system $\text{FeO-TiO}_2\text{-Fe}_2\text{O}_3$ (fig. 23). There are the strongly magnetic cubic oxides magnetite (Fe_3O_4), maghemite ($\lambda\text{-Fe}_2\text{O}_3$), and the solid-solution series of magnetite with ulvöspinel (Fe_2TiO_4), which are the titanomagnetites. The somewhat weaker magnetic rhombohedral minerals are hematite ($\alpha\text{-Fe}_2\text{O}_3$) and its solid-solution series with ilmenite (FeTiO_3), known as titanohematites. Oxidation of these minerals proceeds in the direction of the arrows (fig. 23).

The strongly ferromagnetic magnetite and the paramagnetic (room temperature) and antiferromagnetic (low temperature) ulvöspinel form the end members of their solid-solution series. The variations of Curie point with mole fraction of Fe_2TiO_4 of this series are shown in figure 24.

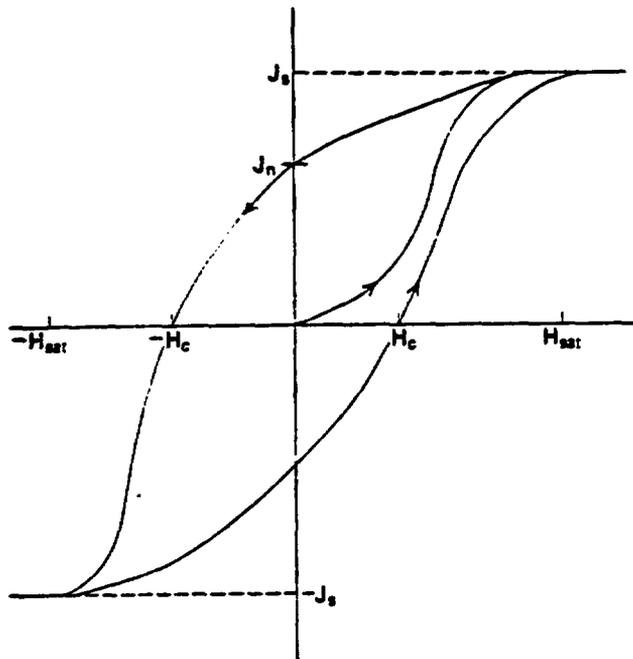


Figure 20.—Hysteresis curve of a ferromagnetic material. J_s is the saturation magnetization, J_n is the remanent magnetization, H_c is the coercive force, and H_{sat} is the field necessary to produce J_s .

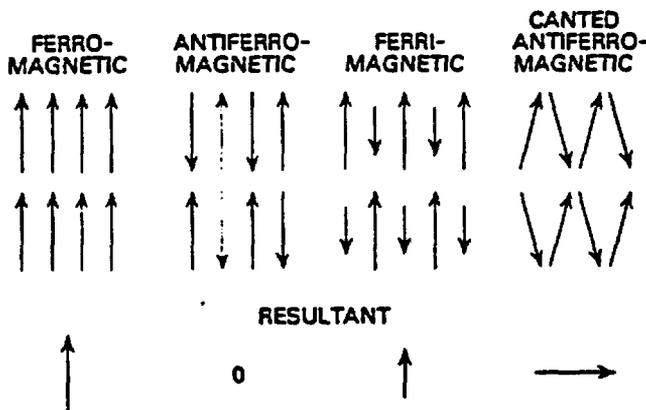


Figure 21.—Types of magnetization and resulting "net" magnetization. Arrows represent atomic moments.

This series is mainly responsible for the magnetization in young basic rocks and can also occur in older volcanic rocks, although they are typically associated with other minerals resulting from subsequent alteration.

Maghemite is also a ferromagnetic, cubic mineral, but is metastable and breaks down into hematite upon heating to above 350°C . Maghemite is generally considered as a "secondary" form of

magnetization produced by low-temperature oxidation of magnetite. This occurrence is generally due to weathering or later stages of slow, initial cooling. In addition, low-temperature oxidation of titanomagnetite can produce titanomaghemite, which is also unstable at elevated temperatures.

Hematite has a rhombohedral structure and both a weak ferromagnetism due to the spin-canting in its two sublattices and a defect ferromagnetism arising from the interaction between the antiferromagnetism and lattice defects or impurities. Ilmenite, which is antiferromagnetic at room temperature and paramagnetic at liquid-nitrogen temperatures, forms the other end of a solid-solution series with hematite. The variation of curie point with mole fraction of FeTiO_3 is shown in figure 25. The unusual solvus curve is shown in figure 26. In the composition range of 0 to 50 percent ilmenite, the solutions behave as canted antiferromagnetic, whereas between 45 and 95 percent ilmenite, they become ferrimagnetic, reverting to antiferromagnetism near 100 percent ilmenite. This series is mainly responsible for the magnetization of red sediments and felsic volcanic rocks.

The only iron sulfide that is ferrimagnetic is pyrrhotite (FeS_{1-x} where $0 < x < 1$). It has an intermediate composition between troilite (FeS) and pyrite (FeS_2). An increase in the sulfur content of troilite causes vacancies to replace the iron atoms, which have ordered locations. Particularly in the region of $x = 0.14$, pyrrhotite is strongly magnetic. Uncertainties exist about its curie temperature, but it is commonly found to occur between 300° and 350°C . In most terrestrial rocks, the iron sulfides appear as pyrite, which has a cubic structure and is non-magnetic. Troilite occurs commonly in meteorites and lunar samples. Its presence causes considerable problems in attempting to thermally demagnetize lunar samples, because troilite immediately begins to break down into pure iron at only moderate temperatures of around 200°C .

Two important, naturally occurring oxyhydroxides of iron, which dehydrate to oxides at 100° to 300°C , are goethite ($\alpha\text{-FeOOH}$) and lepidocrocite ($\gamma\text{-FeOOH}$). Chemically precipitated ferric hydroxides in sediments may suffer dehydration during compaction or much later, forming hematite from goethite or maghemite from lepidocrocite. These types of alterations tend to further complicate the paleomagnetism of red beds which is discussed later.

Thermoremanent magnetization (TRM)

TRM is that remanence acquired by a rock upon cooling from above the curie point to room temperature in the presence of a magnetic field.

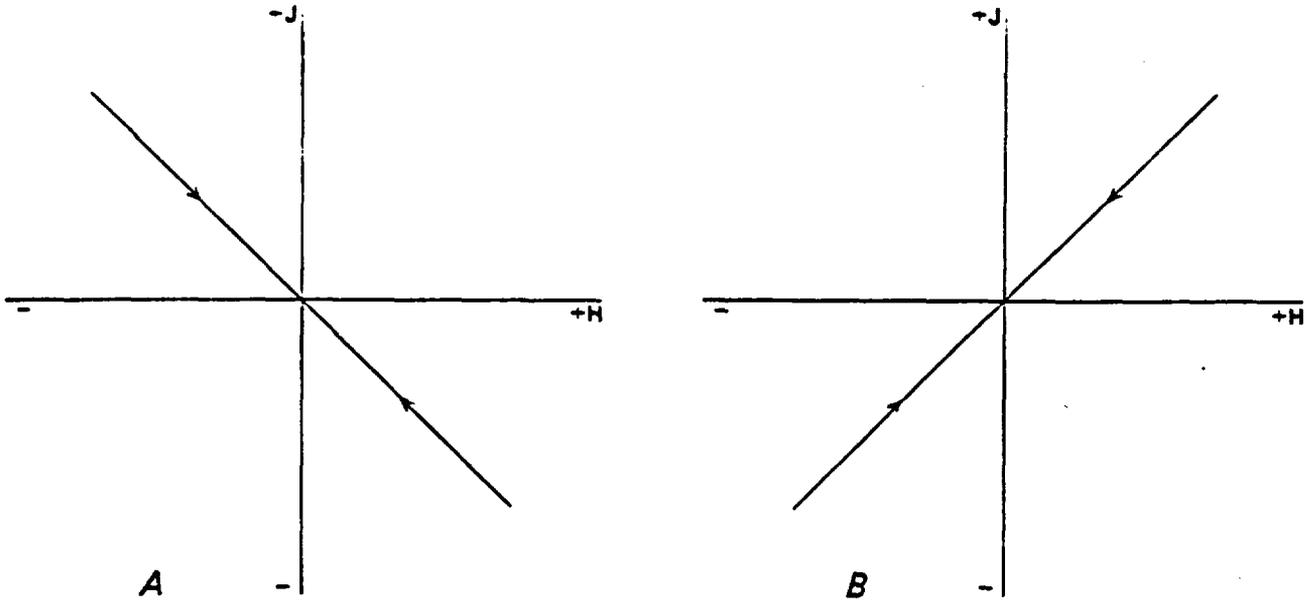


Figure 22.--Graphical representation of the effect of inducing fields on the dipole moment of an atom. A, diamagnetic materials; B, paramagnetic materials. *J* is the magnetization and *H* is the inducing field.

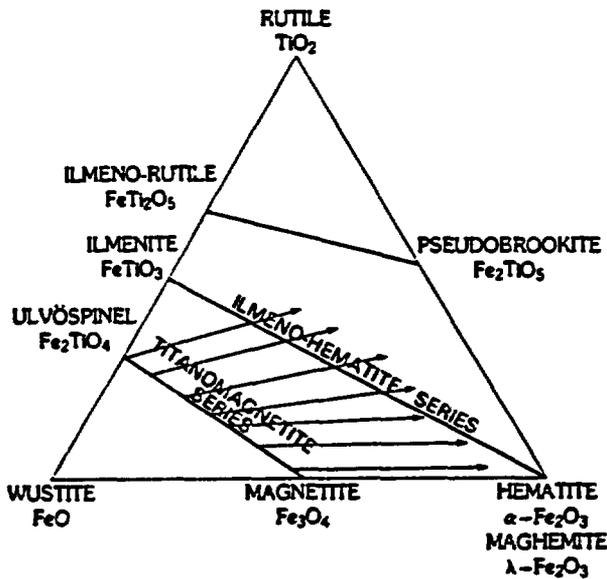


Figure 23.--Ternary diagram of typical iron-titanium solid-solution series. Arrows represent directions of oxidation.

It is considered to be an extremely stable magnetization over the geologic time scale. TRM is not all acquired at the curie point, T_c , but over a range of temperatures down to room temperature (fig. 27). The TRM can be considered to be acquired in discrete temperature intervals, and that fraction of total TRM acquired in each temperature interval is called the PTRM (partial TRM) for that interval. The acquired

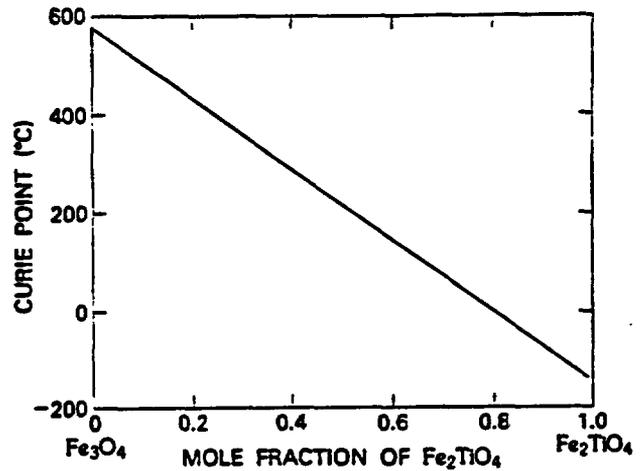


Figure 24.--Variation of curie temperature as a function of magnetite-ulvöspinel ratios.

PTRM depends only on the magnetic field applied during that interval and is not affected during any other subsequent intervals. The total TRM is equal to the sum of the PTRM's. This is known as the law of additivity of PTRM and is an extremely useful principle when applied to paleointensity determinations and thermal demagnetization (Thellier and Thellier, 1959).

TRM acquisition is also a function of grain size (fig. 28), increasing with decreasing grain size. In low fields TRM is proportional to the applied field, but in stronger fields it saturates (fig. 29).

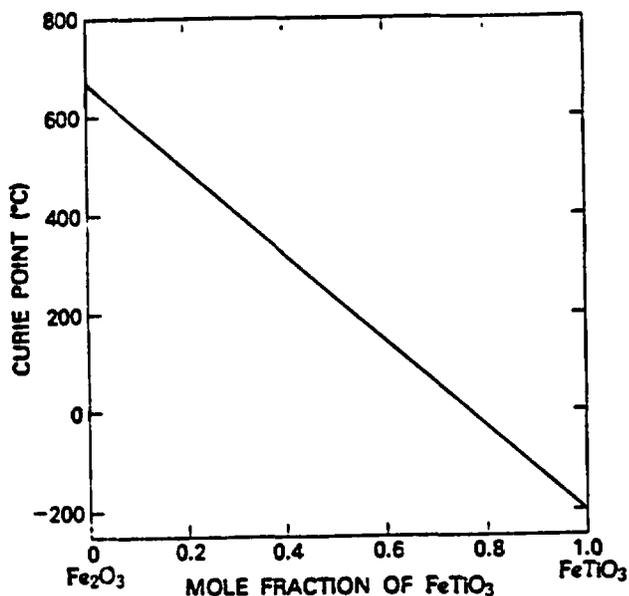


Figure 25.--Variation of curie temperature as a function of ilmenite-hematite ratios.

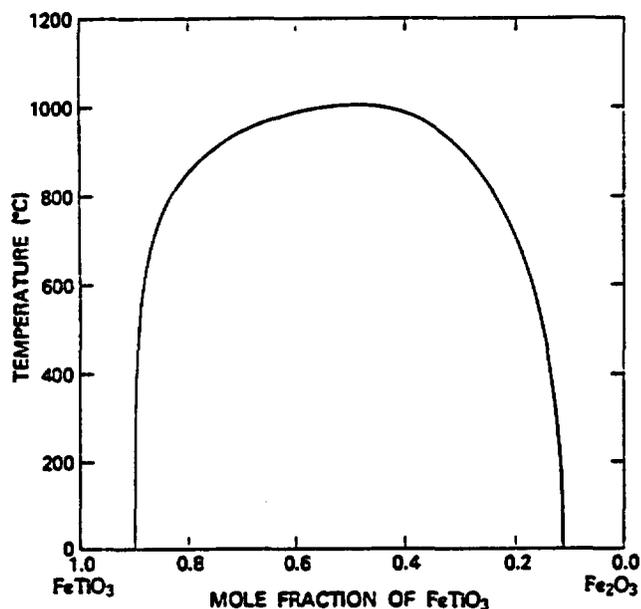


Figure 26.--Solvus curve of ilmeno-hematite solid-solution series.

Chemical remanent magnetization (CRM)

CRM occurs during the formation of a magnetic mineral at low temperatures (ambient) by chemical or phase change in the presence of an applied field. The main products of chemical alteration are hematite, maghemite, or titanomaghemites. These end products can be formed by

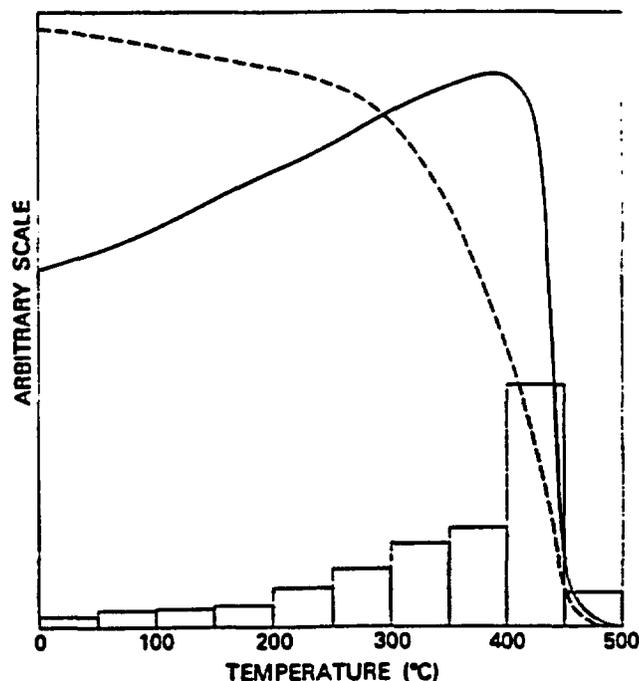


Figure 27.--Representative thermal demagnetization curve showing loss of TRM (thermal remanent magnetization) (dashed curve) and susceptibility (solid curve). Patterned blocks illustrate acquisition of PTRM (partial thermoremanence) by cooling in a magnetic field for different temperature intervals.

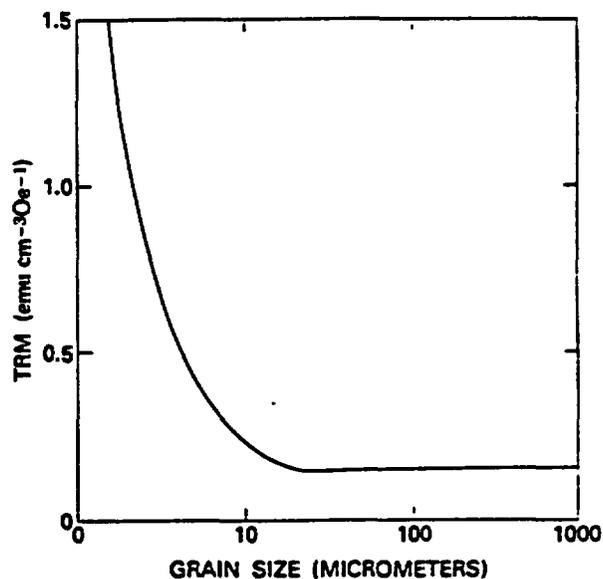


Figure 28.--Acquisition of TRM (thermo-remnant magnetization) as a function of grain size.

any of the following processes: (1) oxidation of magnetite to hematite or maghemite, (2) oxidation of titanomagnetite to titanomaghemite, (3) dehydration of iron oxyhydroxide to hematite, and (4) precipitation of ferromagnesian minerals, such as biotite, hornblende, and augite, from infiltrating ground waters in sediments, and then subsequent oxidation to hematite.

CRM is the most probable source of magnetization in red beds. This is due to unusually large volumes of hematite in the form of either pigmentation or specularite. The intensity of magnetization of red beds can be two or three orders of magnitude greater than that of non red beds. The current controversy in red-bed magnetics is whether the CRM was acquired at, or shortly after, deposition or by subsequent alteration much later (Helsley and Shoemaker, 1973; Larson and Walker, 1975).

CRM acquisition is analogous to the acquisition of TRM. Secondary hematite forms from a nucleation process. At first the grains are so small (<0.02 μ m) that they are superparamagnetic and, therefore, cannot retain a spontaneous magnetization. As the grain grows beyond a critical blocking diameter, the magnetization becomes spontaneous.

Detrital remanent magnetization (DRM)

The process of alinement of all magnetic particles by a magnetic field as they fall through water and(or) the rotation of such particles into the field direction when they are in the water-filled interstitial holes of a wet sediment is called DRM. The original magnetization of all sediments is due to DRM, but in the case of altered sediments, such as red beds, the CRM component soon dominates that of the DRM. Geologically recent lake sediments, however, appear to still carry most of their remanence in the form of DRM, and many investigators are now using such sediments as a tool for analyzing prehistoric secular change of geomagnetic field. Most DRM's are also subject to later viscous effects because of their already weakly magnetic characteristics.

MEASUREMENT TECHNIQUES AND INSTRUMENTATION

Sample collection and preparation

Sample collection is a critical and all-too-often neglected aspect of rock magnetism. At each field site one or more oriented samples are collected, either as an oriented block or an oriented core drilled from an outcrop. From each of these samples, a number of specimens are drilled or sliced. It is absolutely necessary that the samples be collected from an outcrop that is still in situ, because most paleomagnetic studies require referencing the direction of magnetization in the specimen back to the present direction of the geomagnetic field at the sampling site.

Hand sampling of oriented blocks requires using a Brunton compass and inclinometer, for instance, to place at least two horizontal marks on two approximately perpendicular sides of the block and an arrow on the top of the block referencing magnetic north (fig. 30). Field notes should be made as to the dip and strike of the unit sampled. Generally, because of the lack of convenient flat surfaces on the block and errors in compass readings, the accuracy of this method is at best only a couple of degrees; one can overcome these problems, however, by using a simple sun-compass device (fig. 31). A more critical objection to block sampling is that the most convenient samples to collect are sometimes associated with joints or cracks in which surface weathering is more predominant.

The most accurate way to sample is by using a portable core drill (fig. 32); this permits sampling away from undesirable joints and fractures and to greater depths in the outcrop, which are removed from weathering. After the core is drilled and prior to breaking it off from the outcrop, a long tube with an orientation table on top is slipped over the core (fig. 33). The long tube (copper or brass) has a slit down its side for marking the core after the table is oriented. This orientation is accomplished by first leveling the table and recording the dip of the tube, using the protractor on the side. Then the orientation of the table with respect to magnetic north is accomplished using either a Brunton compass or sun compass.

For some studies in which one wishes only to measure the magnetic properties of the rocks, for instance, the rocks do not have to be oriented, but it may be necessary to keep accurate field notes as to the relative stratigraphic and geographic locations of the samples. For susceptibility measurements, the collection of powdered samples may be satisfactory if competent samples are unobtainable.

After the samples have been taken to the laboratory, they probably must be further prepared for measurement of remanence. If hand samples were collected, then specimen cores must be obtained from them. The standard core size required for most measurements in the rock magnetism laboratory is approximately 2.54 cm diam x 2 cm long. The hand sample must be leveled in the laboratory, using a leveling clamp (fig. 34), and cored in the drill press. Prior to breaking off the specimen from the block, the north orientation is transferred to the core. The specimens must then be sliced to proper length using a diamond cut-off saw. If cores were taken in the field, then they need only be cut to proper length.

Preparation of magnetic separates and polished sections

Magnetic separates are needed for any of the following: (1) curie temperature determina-

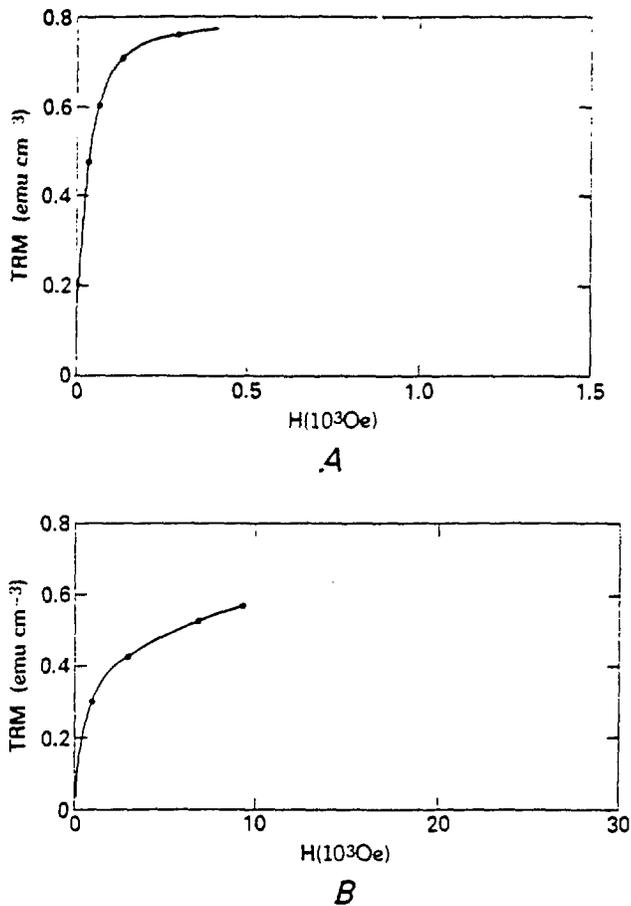


Figure 29.--Acquisition of TRM (thermo-remanent magnetization) in increasingly larger inducing magnetic fields (H). A, magnetite powder; B, hematite powder.

tion, (2) petrographic studies, (3) X-ray diffraction or microprobe analysis, or (4) scanning electron microscope studies. Powdered separates can be obtained in the rock magnetism laboratory in several ways, but they all start with pulverization, using a mortar and pestle. Next one must extract the maximum amount of the magnetic particles possible from the crushed powder. This is generally accomplished by (1) mixing the powder with a beaker of clean water; (2) wrapping a suitably sized permanent magnet with thin plastic; (3) dipping the magnet, enclosed in plastic, into the powder mix and stirring the mixture slowly; (4) slowly removing the magnet with attached magnetic particles and immersing it into another beaker of clean water; and (5) removing the magnet from within the plastic and swirling the plastic around to detach particles, allowing them to settle to the bottom of the beaker. The plastic-wrapped magnet is then returned to the powder-water mixture and the process is repeated until a desired amount of magnetic material is collected. The water from the final beaker is poured off slowly, while

retaining the magnetic particles as a sediment. Acetone is then used to flush the particles from the beaker to a petri dish where the acetone is allowed to evaporate, leaving behind the magnetic particles.

A new way of extracting magnetic particles from a powder has been developed in the rock magnetism laboratory. This method is much simpler because it is done dry. It makes use of the concept of a linear induction motor in which the

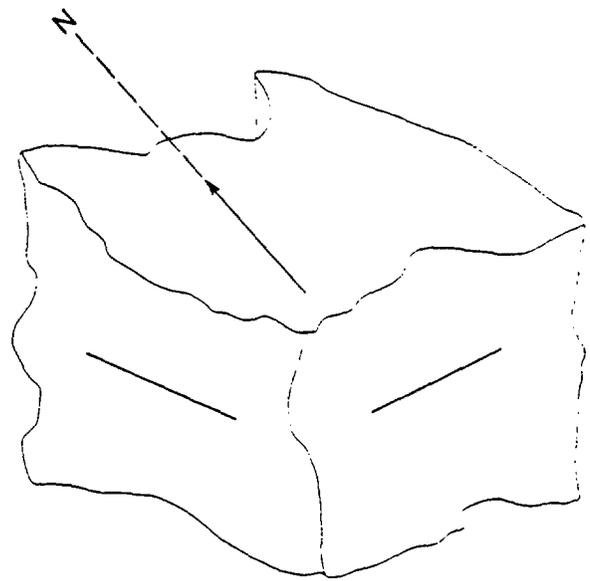


Figure 30.--Drawing illustrating typical method for orienting hand specimens. N represents magnetic north and lines on sides of specimen reference horizontal.

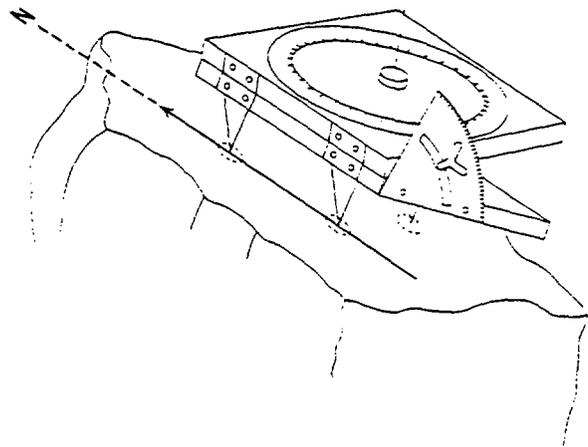


Figure 31.--Sun-compass orientation device. The three pointed legs are used as references. Line drawn on rock points to magnetic north.

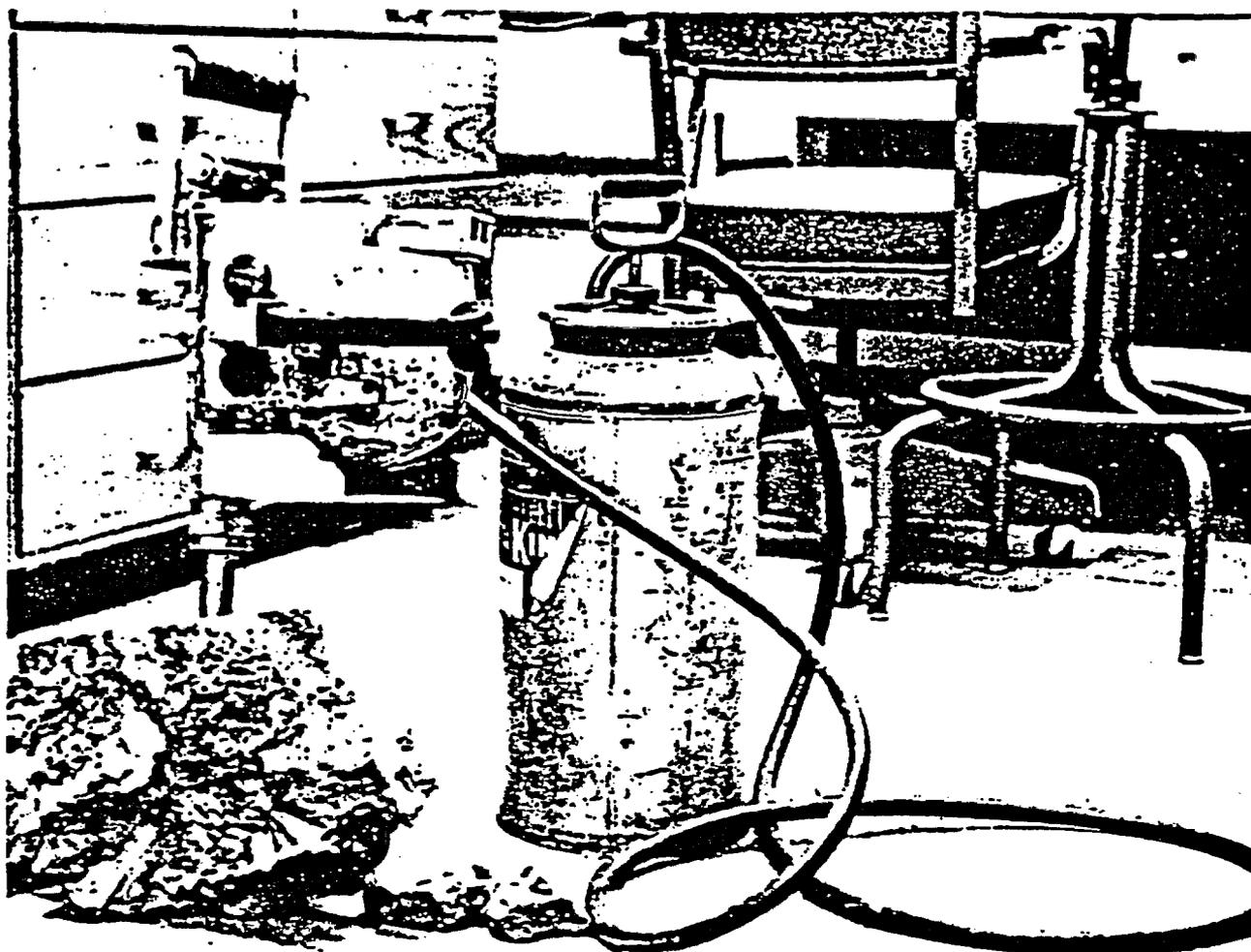


Figure 32.--Light-weight, gasoline-powered, portable drill with auxiliary water supply.

particles become moving magnets driven by a series of coils powered by a three-phase alternating current. The whole-rock powder is simply deposited at one end of this magnetic "conveyor belt," and the magnetic particles move to the other end and are collected in a sample holder, leaving behind the nonmagnetic material.

In addition to the equipment for producing magnetic separates, the rock magnetism laboratory has all the necessary equipment for preparing polished sections of these separates (fig. 35).

Measurement of remanence

The measurement of remanent magnetization constitutes the majority of measurements done in the laboratory. This is accomplished by either of our two spinner magnetometers. One is a standard commercial system with a sensitivity of approximately 10^{-7} emu/cc (fig. 36). It also has the capability of measuring anisotropy of

susceptibility. The device accepts our standard specimen size, and the direction and intensity of magnetization in the rock can be obtained by either a three- or six-spin set of measurements (fig. 37). Six-spin measurements are usually required when dealing with specimens whose remanent intensity falls below 10^{-6} emu/cc. A digital readout is provided for additional accuracy. Computer programs for determining resultant directions and intensities along with complete statistical analysis, including paleopole positions, are available on a hand calculator with printout.

The second spinner magnetometer is a new digital system (fig. 38). The digital spinner is faster and more sensitive (2×10^{-8} emu/cc), using the same measuring techniques; that is, fluxgate sensor, magnetic shield, and 5-Hz drive assembly. However, the computerized system differs from the analog system in that it converts the fluxgate signal into digital form and processes the data in the minicomputer provided



Figure 33.--Core orientation device. Brunton compass is shown placed on top.

with the system. Instead of locking onto the fluxgate signal and doing a time-dependent integration as in the analog, the digital data from the digital spinner signal are Fourier-analyzed for each spin and averaged for consecutive spins until the predetermined signal-to-noise ratio is met. The digital spinner uses a six-spin set that is slightly different than that of the analog system (fig. 39). A block diagram of the digital system is shown in figure 40.

Measurement of curie temperature

Thermomagnetic analysis based on determination of a rock's curie temperature has become a standard tool for mineral identification (figs. 41 and 42). The procedure involves measuring the saturation magnetization J_s as a function of temperature T . J_s - T analysis can also be used for determining the suitability of samples for paleointensity measurements and for

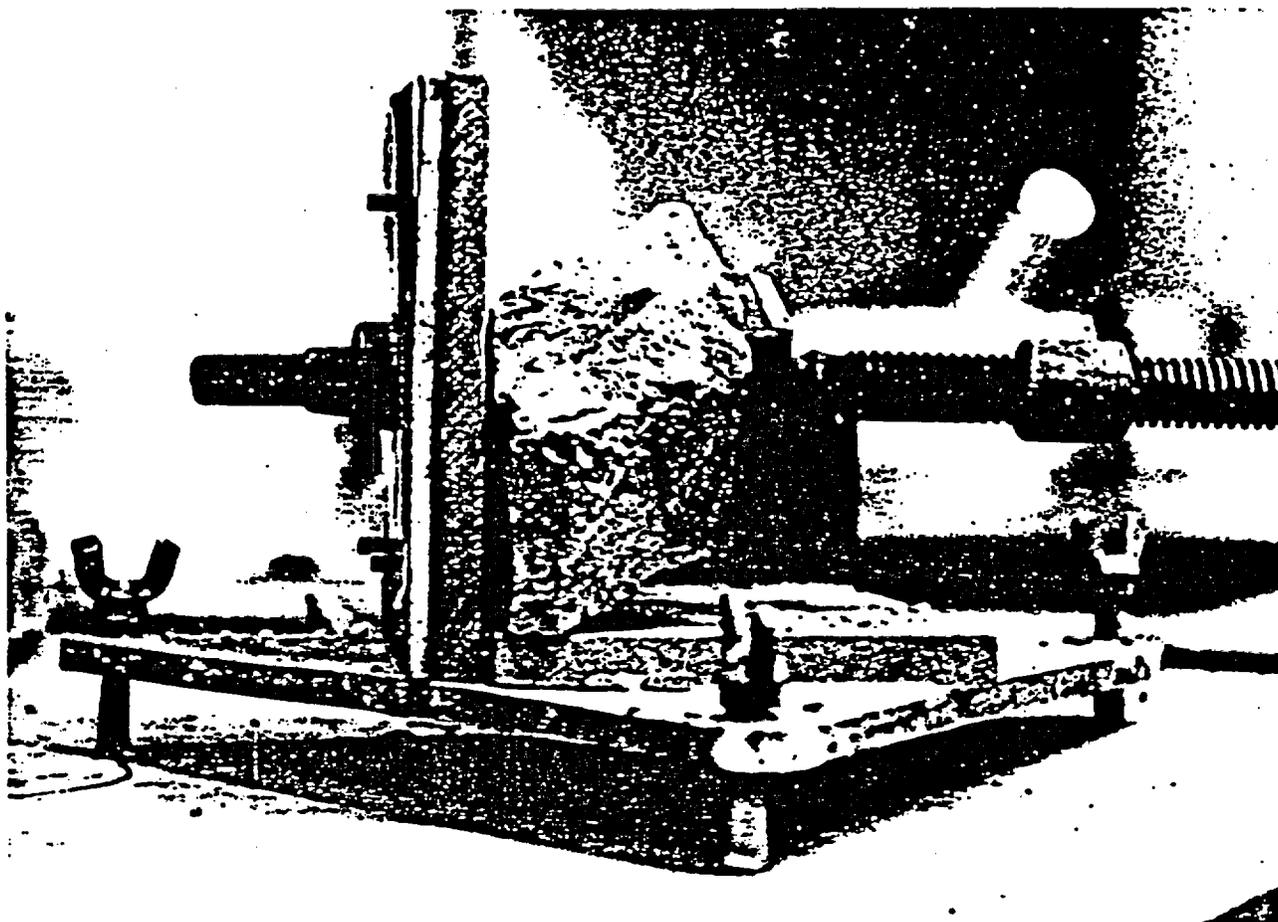


Figure 34.--Laboratory orientation clamp with rock in place.

examining the rates of alteration of a mineral or assemblage of minerals during heating.

The curie balance that is located in the rock magnetism laboratory is shown in figure 41. The heart of the system is an electrobalance that can measure weight changes as small as 5×10^{-7} g. A balance of this type has the advantage of providing a voltage proportional to weight and also of maintaining the sample in exactly the same position between the pole pieces of a magnet during the experiment. This fixed position eliminates the need to adjust for changing field gradients. The modified balance system consists of (1) the electrobalance; (2) a chromel-alumel thermocouple; (3) a furnace with controller capable of reaching 800 C; (4) a 1.8-kilogauss permanent magnet capable of saturating most common magnetic minerals (hematites excluded); (5) an accurate gas-mixing system capable of providing a partial pressure of oxygen in the furnace of from 1 atm down to 10^{-35} atm, thus eliminating the need for a vacuum system; (6) an oxygen fugacity probe that permits the monitoring of the oxygen activity on a real-time basis; (7) an electrometer for measuring the output of the fugacity probe; and (8) an

X-Y plotter that automatically plots J vs T (fig. 42). The furnace, fugacity probe, thermocouple, and gas inlet are all incorporated into the probe assembly (fig. 43).

The fugacity probe is an yttria-doped zirconia ceramic electrolyte (Sato, 1970) that functions as follows: the tube is closed at one end, and gold or platinum-foil electrodes are fitted to the inside and outside of the closed end of the tube. Pure oxygen is fed into the inside of the tube furnace. Any difference in total oxygen between the reference and the external gas mixture causes charged oxygen ions to migrate, creating a potential difference between the two electrodes. This potential is measured by an electrometer. The oxygen fugacity can be calculated using the thermodynamic equation:

$$-\log f(O_2) = \frac{(E \text{ in mv}) \times 100}{(T \text{ in K}) \times 4.96} \quad (3)$$

A typical measurement of the curie temperature of a specimen proceeds as follows: the specimen is prepared either in the form of chips from a whole rock or a powdered magnetic separate from a sediment. Depending upon how strongly magnetic the specimen is, one chooses

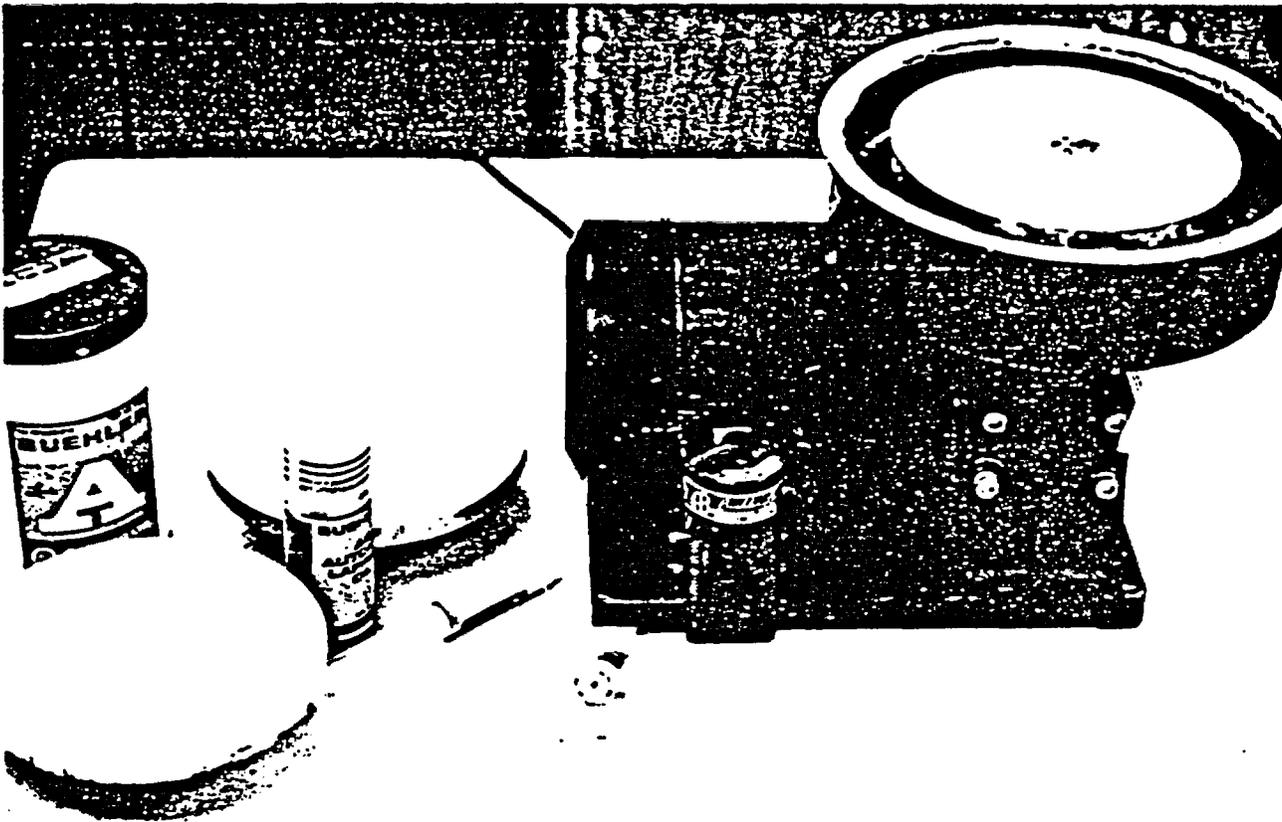


Figure 35.—Polisher with accessories and various polishing compounds.

the amount of the material to be measured; this can range anywhere from a single grain weighing several micrograms to a quantity of powder weighing as much as a few hundred milligrams. One must optimize this amount to prevent the suspension system from being drawn to the side of the furnace by the magnetic attraction of the permanent magnet. The specimen is then placed in the small quartz bucket, the furnace unit is attached, and the specimen is weighed and zeroed, using the digital tare provided by the Cahn electronics to give a zero reference on the recorder. The magnet is then moved into position. An apparent weight increase will be due to the downward force on the magnetic materials generated by the vertical gradient between the poles of the magnet. The furnace controller is then set at the desired final temperature, the current to the furnace that is necessary to achieve that setpoint is set, and the furnace is turned on. When the setpoint is reached, the furnace is switched off and allowed to cool to room temperature. A typical direct plot of a run is shown in figure 44. If gas control is desired during a run, the gas mixture must be flowing (approximately 60 mL/min) before the specimen is weighed, so that the small amount of buoyancy created by the upward-flowing gas can be canceled along with the weight.

Magnetic cleaning of specimens

Introduction

The main objective behind magnetic cleaning of rock specimens is to remove unstable or unwanted secondary components of magnetization that have been added subsequent to the formation of the original or primary magnetization. Even the primary magnetization may be unstable. In these cases, the results of magnetic cleaning could indicate sufficient uncertainty in the data so as to warrant their being discarded. Apart from an interest in the stability of rocks, an understanding of the origin of the magnetization being studied is important. Magnetic cleaning can provide additional clues.

Secondary components can appear in several forms. IRM (isothermal remanent magnetization) is formed by large magnetic fields at ambient temperatures. An example of this is lightning strikes. VRM (viscous remanent magnetization) is formed in relatively weak fields over long periods of time as a function of temperature. Chemical remagnetization can create still another form of secondary magnetization. However, this form is stable, sometimes even completely overprinting the primary magnetization.

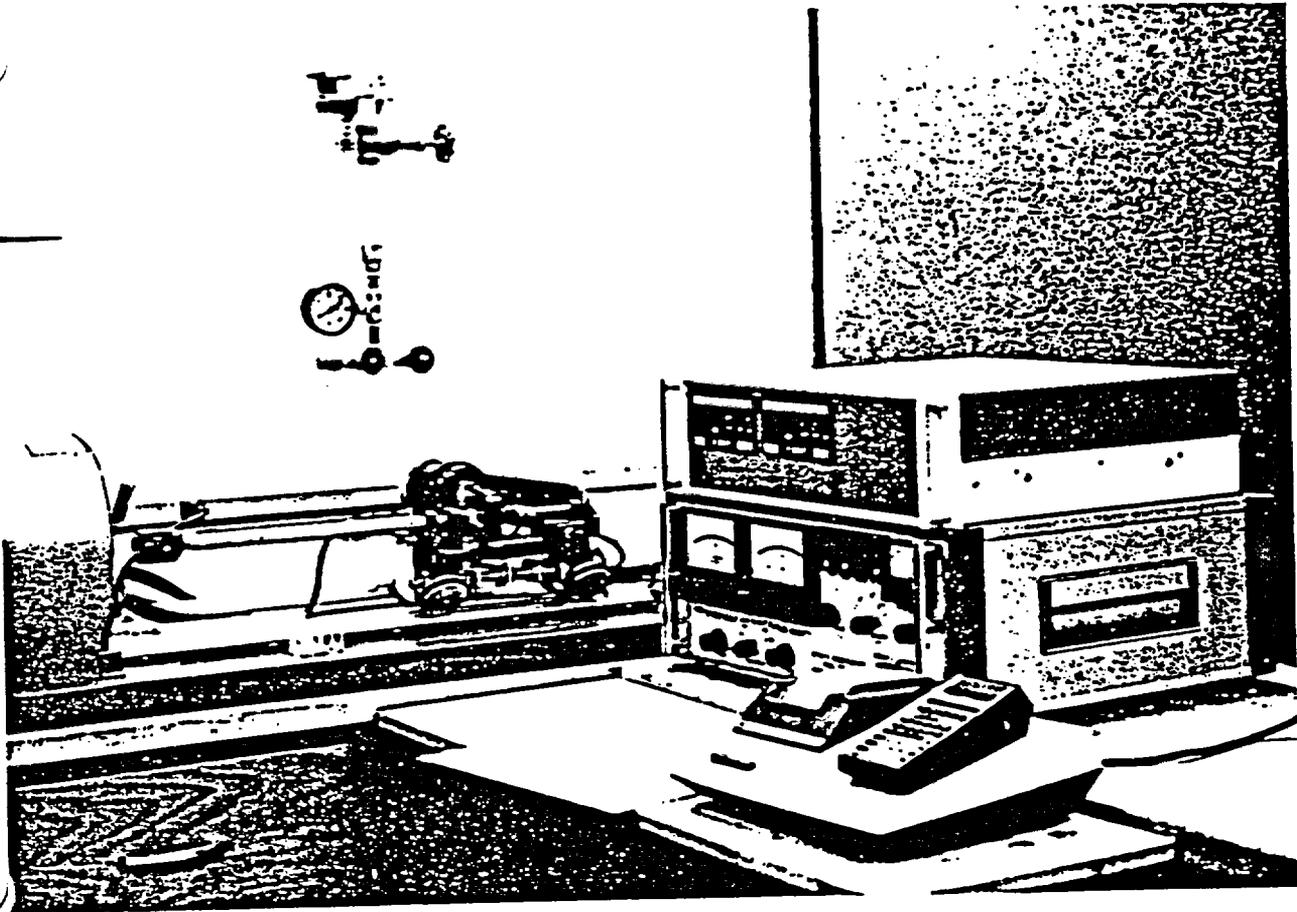


Figure 36.--Standard analog spinner magnetometer.

Alternating-current demagnetization

The energy required to change the magnetic state of a specimen may be supplied by a magnetic field, and the "coercive force" (fig. 20) indicates the strength of field necessary to induce a magnetic change. The average coercive force is easily measured for a rock and varies from tens to thousands of oersteds, depending upon grain shape, size, alinement, and degree of internal imperfections. Because of the wide spectrum of microscopic coercivities in a rock, progressive demagnetization, first of softer regions, then of harder ones, can be carried out. A direct field does not discriminate the varying hardnesses, but if a rock is subjected to an alternating field in such a way that the magnetized zones are affected by many cycles of diminishing amplitude of field, these softer zones will be magnetized into random orientations that cancel, while the harder ones remain unmodified. The a.c. (alternating-current) demagne-

tizer in the rock magnetism laboratory consists of (1) a solenoid (coil constant of 125 Oe/amp) capable of fields to 850 Oe without appreciable overheating, (2) a three-axis tumbling mechanism, and (3) a solid-state 60-Hz power supply that drives the coil from some preset current to zero (<1 ma) linearly with time (fig. 45). The rate of demagnetization is 100 Oe/min. A typical a.c. cleaning proceeds as follows: after measurement of the NRM of a specimen, it is placed in the tumbler. A peak field (perhaps 25 Oe, 50 Oe, or 100 Oe) is chosen and the time of decay is set. First the tumbler is turned on; then the start switch is thrown. The rock tumbles as the field decays to zero. The start switch is then turned off, followed by the tumbler. The rock is removed and placed back in the spinner to measure the new remanence. This process is repeated at progressively higher magnetic fields until the desired results are obtained. These are explained in the data analysis section of this report.

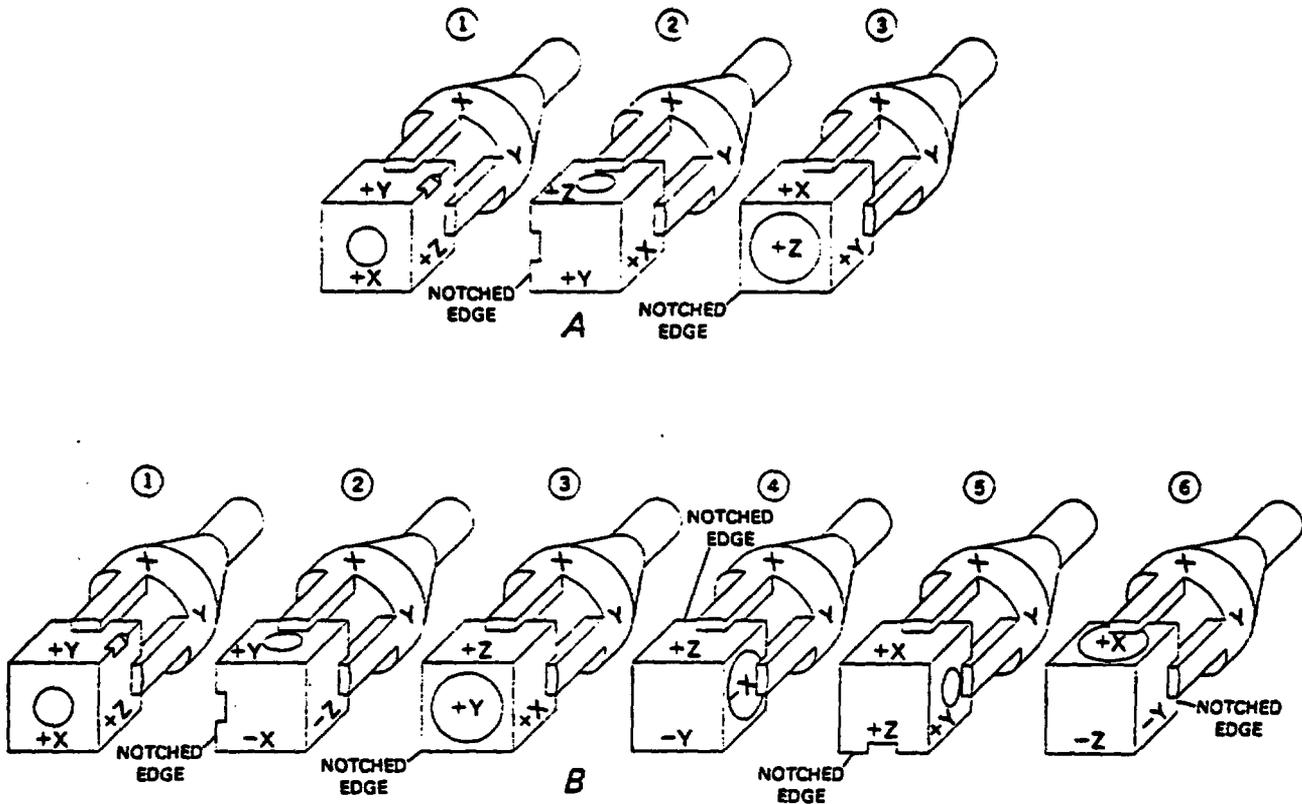


Figure 37.—Specimen orientation for the spinner magnetometer. A, three-spin orientation; B, six-spin orientation sequence.

Thermal demagnetization

The characteristic time for a process, which appears as a relaxation time in theories of magnetic viscosity or thermoremanence in single domains, is:

$$t = \frac{1}{c} \exp \frac{vH J}{2k\tau} \quad (4)$$

where k is Boltzmann's constant and τ is $^{\circ}\text{K}$. The blocking temperature for a grain of volume v is that temperature at which the relaxation time t becomes small, say 100 sec. A high blocking temperature indicates that the grains will have a long relaxation time at room temperature. The blocking-temperature spectrum of a rock can be broken into two basic parts: thermally discrete components that have high stabilities which remain unchanged up to the curie temperature; and thermally distributed components that consist of a series of blocking temperatures and are less stable and, therefore, more capable of acquiring secondary components of magnetization.

If the specimen temperature is raised in discrete steps, the transitions that have short relaxation times will occur at lowest temperatures. These will be demagnetized if the specimen is in a zero magnetic field during cooling.

Unstable or secondary VRM or IRM can be demagnetized while magnetically harder components remain essentially unchanged. Examples of thermal demagnetization of TRM, IRM, and CRM are illustrated in figure 46 for comparison.

The rock magnetism laboratory contains two complete thermal demagnetization systems. One is a single-sample, platinum-wound furnace (fig. 47) with atmospheric control identical to that included in the curie balance. The temperature controller has a $\pm 1^{\circ}\text{C}$ accuracy and uses a platinum-platinum thermocouple. The furnace is surrounded by a two-layer mu-metal shield that lowers the ambient field around the sample to within ± 2 gamma. There is, in addition, a set of axial Helmholtz coils interior to the shields for the purpose of applying as much as a 1 Oe field for paleointensity measurements.

The second thermal demagnetization system is a multisample (as many as to 12) cylindrical furnace (fig. 48). The temperature controller has a $\pm 1^{\circ}\text{C}$ accuracy and uses a chromel-alumel thermocouple. Over the entire area containing the samples (approximately 3-in. diameter x 6-in. length), the magnetic field is maintained to within ± 5 gamma. This is accomplished by a two-layer mu-metal shield. A typical heating to 600°C and cooling to room temperature takes about 1 hour.

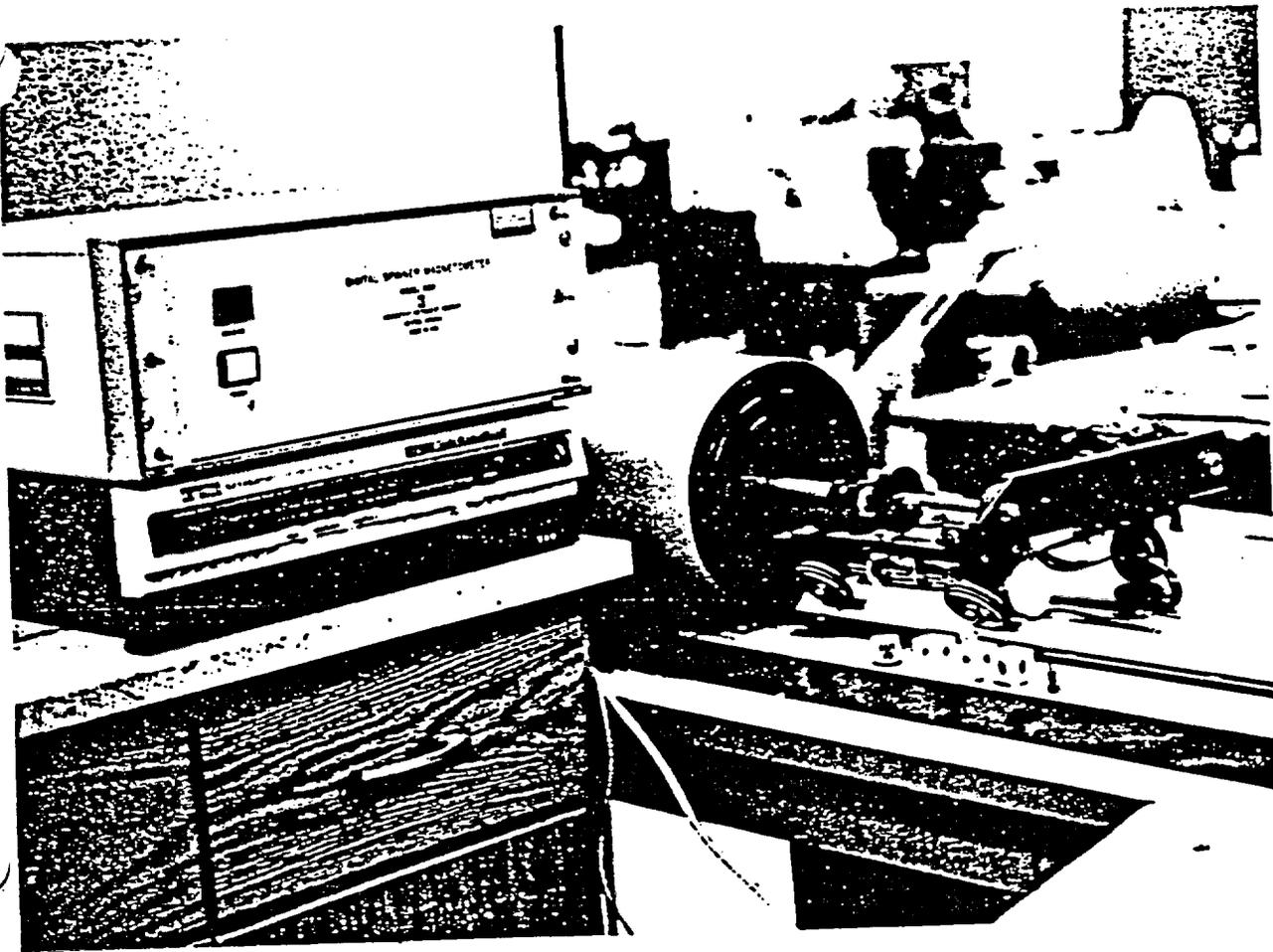


Figure 38.--Digital spinner magnetometer.

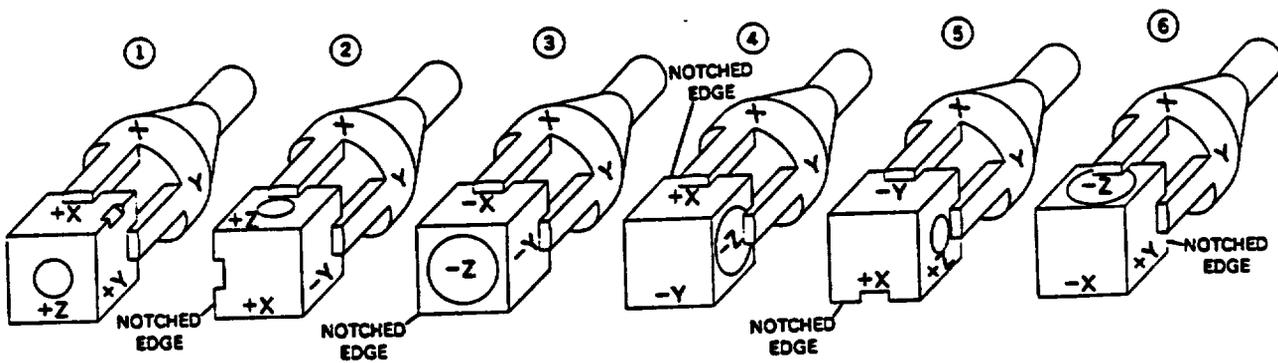


Figure 39.--Sample-holder orientation for spins one through six, as used on the digital spinner.

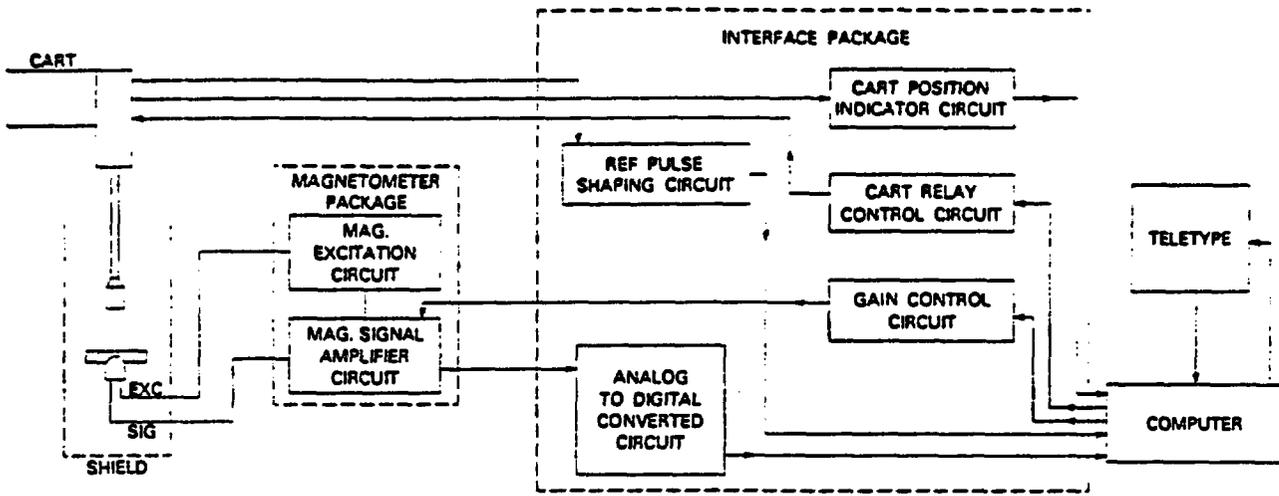


Figure 40.--Digital spinner magnetometer system.

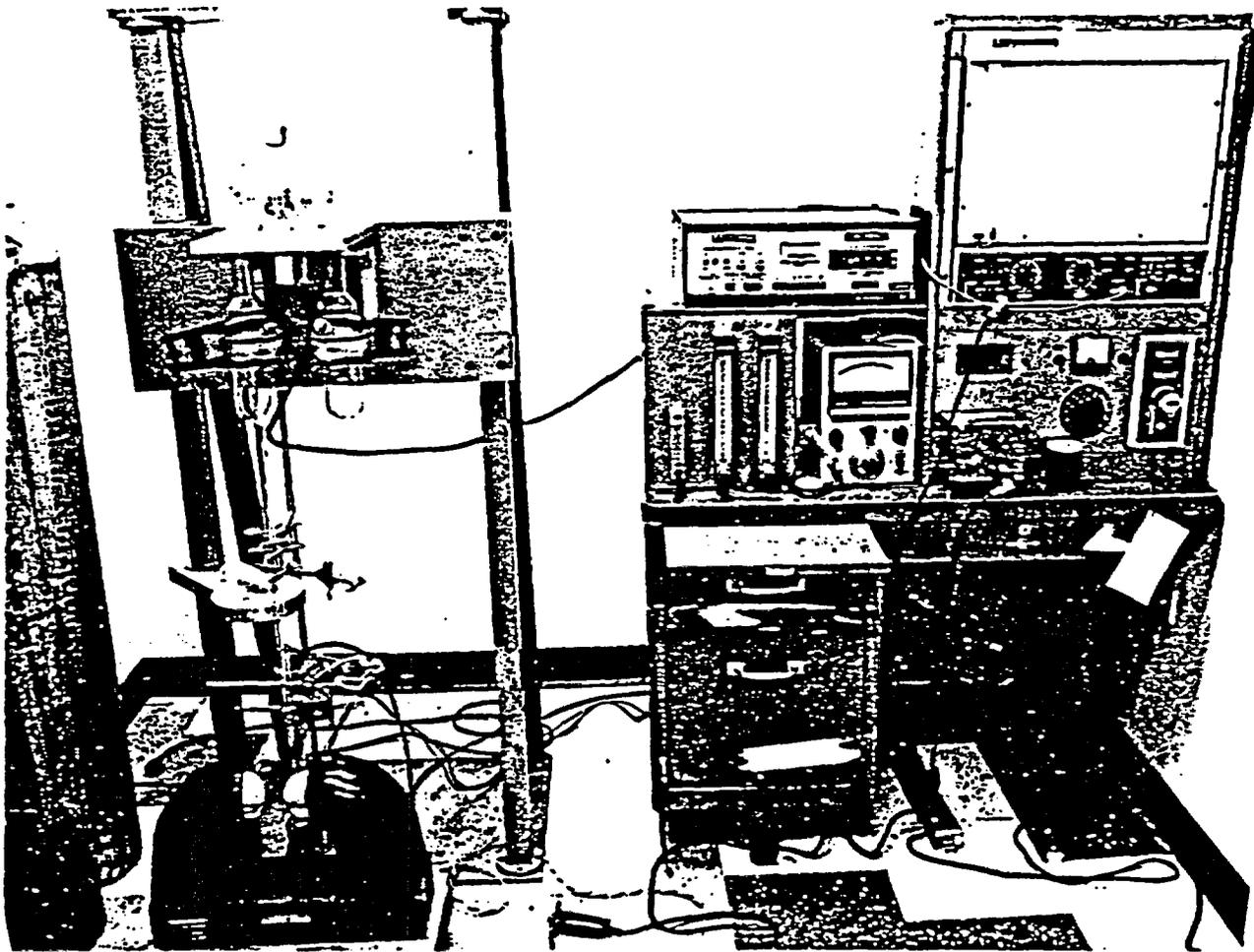


Figure 41.--Curie balance system based on an electrobalance.

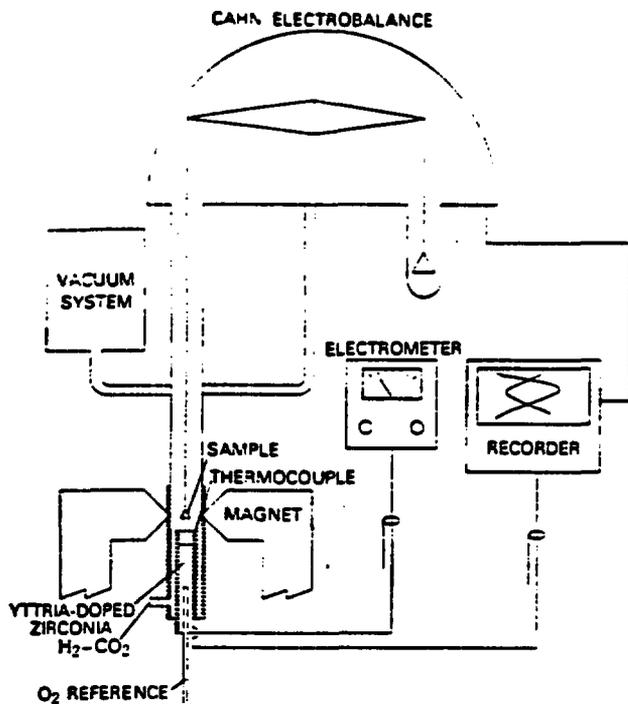


Figure 42.--Schematic of curie balance system.

A thermal demagnetization run proceeds as follows. A specimen or specimens are placed in the spinner magnetometer and the direction and intensity of the NRM's are measured. They are then placed in the furnace and heated to a predetermined temperature step (for example, 100°C) and held. An average 12-cc specimen will take about 30 minutes to equilibrate. The furnace is then shut off and the specimens are allowed to cool to room temperature in an essentially zero magnetic field. They are returned to the spinner for remeasurement of direction and intensity. This process is repeated at higher temperatures until either all of the remanence is destroyed or the objectives of the experiment are achieved. These objectives are discussed in a later section on data analysis.

Petrographic analysis

A thorough investigation of paleomagnetic or rock-magnetic properties should include a petrographic analysis of the specimens used in the study. Curie-temperature determination for the purpose of mineral identification is not sufficient in many cases. For instance, a titanomagnetite containing about 60 percent ulvöspinel has a curie temperature of around 200°C, but so does a titanohematite containing about 50 percent ilmenite. The laboratory has a petrographic microscope for use with either transmitted or reflect light; its highest magnification capability is 600X. In addition, an automatic camera setup is attached to the microscope for either Polaroid or 35-mm pictures (fig. 49).

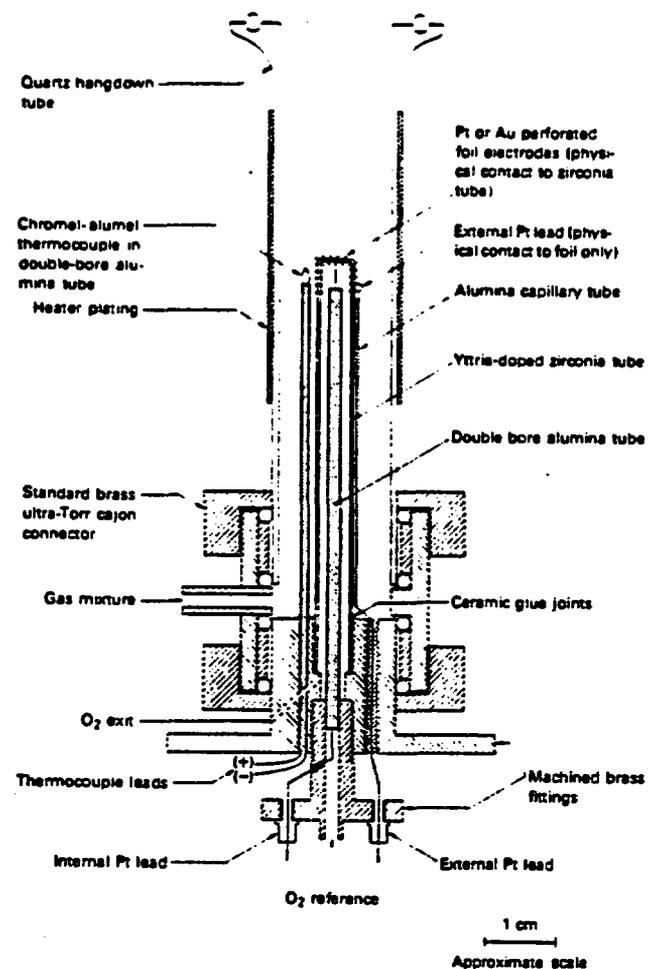


Figure 43.--Miniature oxygen fugacity probe used in electrobalance system. Scale is approximate.

DATA ANALYSIS AND EVALUATION

Field tests for stability

Basic information is required concerning the geologic history of the host rock unit from which the samples were collected. This information will be used in seeking to discover some geologic process that will indicate the time dependence of physical mechanisms in rocks. The purpose of subjecting these rocks to demagnetization and field tests is to determine whether remanent magnetization of a rock was acquired at a specific time and whether it is parallel to the ambient magnetic field operative at that time.

One set of tests is for the self-consistency of the data. For example, samples collected from a single geologic unit or from several units of similar age may be said to be magnetically stable if they have consistent directions of magnetization. Also, normal and

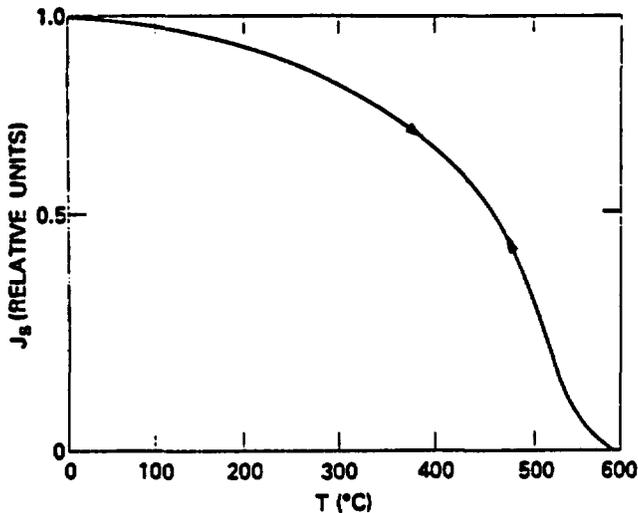


Figure 44.--Typical saturation-magnetization (J_s) versus temperature curve. Arrows indicate reversibility of heating and cooling curves.

reversed directions of magnetization from rocks of similar age, provided that these directions are exactly antiparallel, provide a strong argument for stability. If a single geologic unit is sampled over a large geographical area and consistently uniform directions of magnetization are found, then this strongly indicates stable remanence.

A particularly useful test can be applied to igneous rocks. These have intrusion temperatures higher than the curie temperature of their magnetic minerals. As they are emplaced, they heat the surrounding country rock to temperatures sometimes exceeding the curie temperatures of the minerals in the country rock. On cooling, the direction of the ambient field may be locked into both units. If the igneous unit and the baked contact have the same direction of magnetization, they can be considered to be stable.

The above tests relate to possible alteration of the magnetic minerals with time. Other tests reflect stability even though the rocks may have been physically displaced by some geologic process. The most common of these is the fold test. If a formation has been folded and the directions of magnetization are corrected for structural attitude, all the directions should be the same if they were acquired prior to folding and have been stable since. The conglomerate test has also been used on occasion. If pebbles in a conglomerate can be identified with an older source formation and these pebbles have random directions of magnetization, then it can be said that the magnetic minerals in the pebbles have been stable over geologic time. This implies that the source formation may be considered stable and suitable for paleomagnetic sampling.

Laboratory tests for stability

One of the simplest types of laboratory stability tests is the storage test. This involves measuring the remanence directions of the samples as soon as possible after returning from the field and then storing them in a known ambient field for some time. The directions are then remeasured periodically for times as short as days to as long as months. If directions remain unchanged, the samples can be considered to be relatively stable. If drastic directional changes occur, especially within shorter periods of time, the samples are magnetically unstable. The above effect is due to the acquisition of VRM. Samples that exhibit this tendency contain minerals with extremely low coercivities.

The most widely used technique for determining the magnetic stability of a rock is a.c. demagnetization. This test consists of submitting the samples to a series of a.c. demagnetizing cycles. The method for determining suitable cycles varies. The best way to describe the methods is through examples. In figure 50A the NRM directions have a pronounced streaking characteristic. Cleaning to 200 Oe causes the directions to group tightly, and going beyond 200 Oe produces no significant improvement. In figure 50B the directions are widely scattered, and at 400 Oe they are grouped. Figure 50A is representative of a VRM component in the direction of the present Earth's field. Figure 50B appears to be due to IRM produced by lightning. These conclusions are supported by the plot of intensity versus peak demagnetizing field (fig. 51). Curve B shows an abrupt initial decrease to 200 Oe with only 5 percent of the original remanence remaining. It is well known that induced IRM can be removed by an equivalent a.c. field up to saturation.

In general, both IRM and VRM tend to be less resistant to a.c. demagnetization than TRM, CRM, or DRM. Therefore, they can be removed selectively while preserving the original magnetization. Also, although both examples in figure 51 tend to stabilize in intensity above 200 Oe, B in figure 50 does not group in direction until about 400 Oe. Much of the subjectiveness enters into the a.c. cleaning procedure at this point. The choice of optimum demagnetizing field is often based upon a combination of criteria. Any one may be objective in nature, but they are typically combined in a subjective manner. Generally speaking, for most rocks, 200 Oe a.c. should be sufficient to remove spurious components of magnetization.

Thermal demagnetization or thermal cleaning is another technique for estimating the stability and determining the original directions of magnetization in rocks. Partial thermal demagnetization is used commonly to remove secondary components with low blocking temperatures and to eliminate the effects of low-tem-

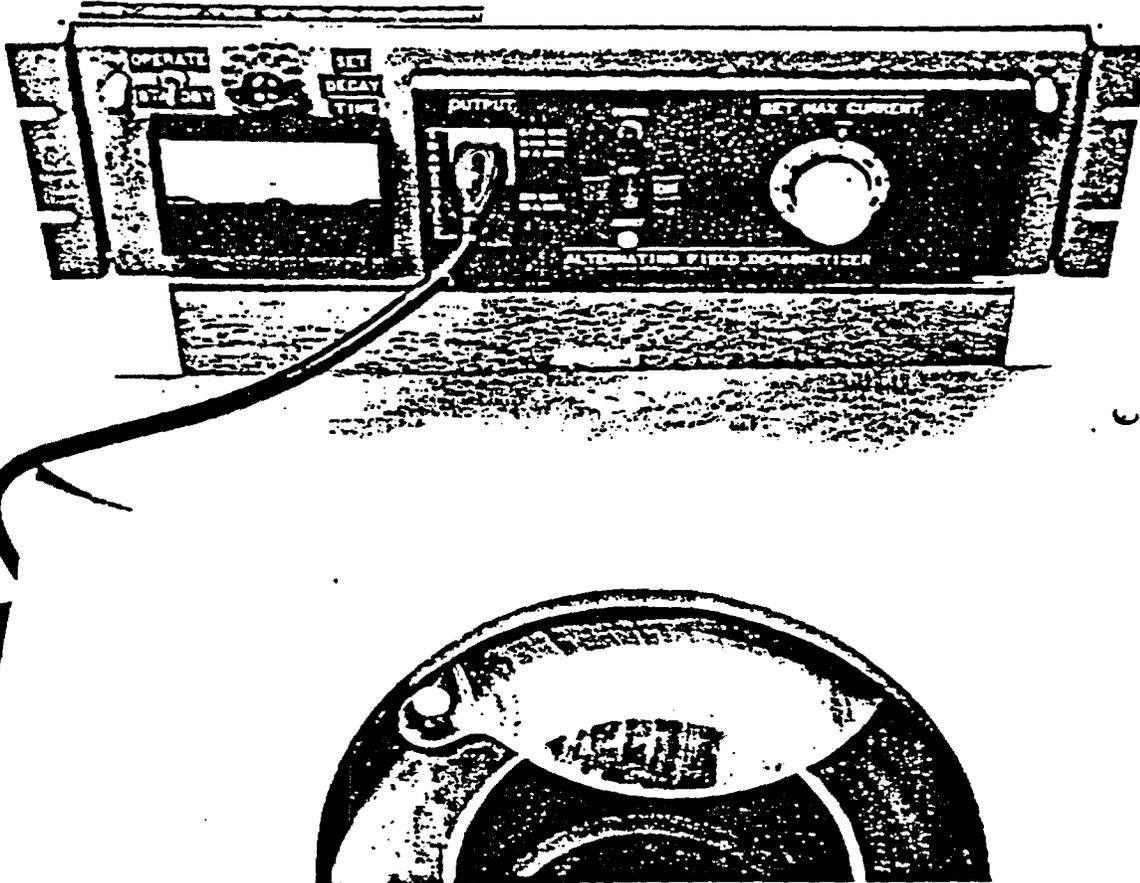


Figure 45.--Alternating-current demagnetizer showing tumbling mechanism in foreground and solid-state controller at rear.

perature thermal overprinting in rocks. Thermal cleaning appears to have little effect on IRM. As with a.c. cleaning, thermal cleaning also requires a bit of subjectiveness. For instance, in dealing with red beds, thermal demagnetization can drastically lower the intensity of a rock in the first few hundred degrees, but the direction of magnetization can continue to change to within 50°C of the curie temperature of hematite (670°C).

None of the above tests should be accepted without a reasonable knowledge of the magnetic minerals of the rock. This can only be acquired from petrographic, X-ray diffraction, and curie-temperature analyses.

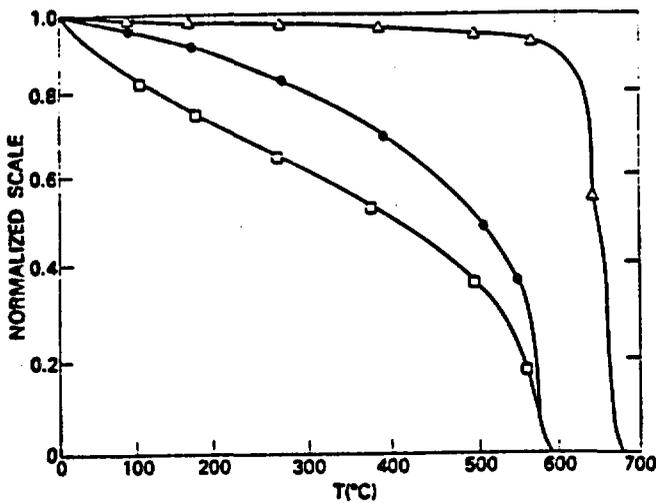
Statistical methods

By examining a list of paleomagnetic directions, poles, and intensities, one can get an

idea of their average value and scatter; but statistical analysis affords the opportunity to compare sets of data and put meaningful numbers on distributions and scatter. Two assumptions that are usually made are that (1) every vector has equal significance and is given equal weight, and (2) the directions have a Fisherian distribution. Fisherian statistics were developed to meet the demand for defining the distribution of points on a sphere (Fisher, 1953).

Directions of magnetization are usually expressed in terms of their declination, which is measured clockwise from true north, and their inclination from the horizontal plane, expressed as positive downwards (fig. 52). Directions of magnetization can also be described as pole positions (fig. 53). The latitude and longitude of this pole (λ_p, ϕ_p) can be calculated from

$$\lambda_p = \sin^{-1} (\sin \lambda_s \cos \psi + \cos \lambda_s \sin \psi \cos D)$$



EXPLANATION

- Total thermoremanent magnetization given to magnetite powder at 600° C
- △— Red sandstone containing mostly hematite
- IRM produced in magnetite powder in field of 100 Oe at 20° C

Figure 46.--Examples of thermal demagnetization of three types of remanence: solid dot, TRM (thermoremanent magnetization) given to a magnetite powder at 600°C; open triangle, CRM (chemical remanent magnetization) hematite in a red sandstone; open square, IRM (isothermal remanent magnetization) produced in magnetite powder in field of 100 Oe and 20°C.

and

$$\phi_p = \phi_s + \delta,$$

where

$$\delta = \sin^{-1} (\cos \psi \sin D / \cos \lambda_p).$$

Here the site location, λ_s, ϕ_s , is known along with the declination D and inclination I. The colatitude or distance of the pole from the sampling site is given by

$$\psi = \cot^{-1} (1/2 \tan I).$$

It is assumed that the remanence was acquired in the field of a uniformly magnetized earth (fig. 53).

Remanence is a vector; therefore, one can obtain a mean direction by standard vector algebra. In cartesian coordinates,

$$x = \cos D \cos I;$$

$$y = \sin D \cos I;$$

$$z = \sin I.$$

and

The resultant vector R and its direction, \bar{D}, \bar{I} , are given by

$$R_2 = (\Sigma x)^2 + (\Sigma y)^2 + (\Sigma z)^2;$$

then

$$\bar{x} = \frac{\Sigma x}{R}; \bar{y} = \frac{\Sigma y}{R}; \bar{z} = \frac{\Sigma z}{R}$$

and

$$\bar{D} = \tan^{-1} \frac{\bar{y}}{\bar{x}}; \bar{I} = \sin^{-1} \bar{z}.$$

Pole positions or directions of magnetization can be shown graphically on many projections. The most common is equal-area (orthomorphic) polar or equatorial stereographic. As a convention, the vectors are plotted as solid circles on the lower hemisphere (positive inclinations) and open circles on the upper hemisphere (negative inclinations).

Fisher (1953) described the mathematics for determining the various statistical parameters that are necessary for the proper evaluation of magnetic-pole data. Those formulas will not be reiterated here, but mention will be made of the types of parameters most commonly used, and examples are shown in figure 54. Five groups of nine points are presented. The table lists, for each group, (1) the vector sum R; (2) the precision parameter K, which determines the dispersion of the points; (3) α_{95} , which is the radius

of a circle on the sphere corresponding to a probability of 0.05, so that there is a 20 to 1 chance of the true mean direction lying within that circle; and (4) the circular standard deviation θ_{63} , which is the diameter of a circle enclosing 63 percent of the points. In general, the larger the value of k and the smaller the α_{95} , the more reliable are the results.

Statistical analyses can be done for different sampling levels (specimens, samples, sites, units, and so forth), or different demagnetization levels, or both. Because the precision of the statistical analysis is dependent upon the number of samples, one might feel that it is necessary to maximize the number collected, but several previous studies have shown the optimum to be six to eight independently oriented samples per unit. If any weighting is done, it is usually accomplished by either eliminating suspect samples from the analysis or using uneven numbers of specimens from each sample.

Two objective measurements of stability have been developed in the last few years: S.F. (the "Stability Factor") is based on the changes in direction and intensity during stepwise demagnetization. For each step (i),

$$S.F._i = \bar{R}_i / (\bar{R}_i + I_r),$$

where \bar{R}_i is the vector at step i and I_r is the nonvector sum of all previous changes. S.F. is essentially a measure of the ratio of low and high coercivity vectors and applies more to magnetic-properties studies. S.I. (the "Stabil-

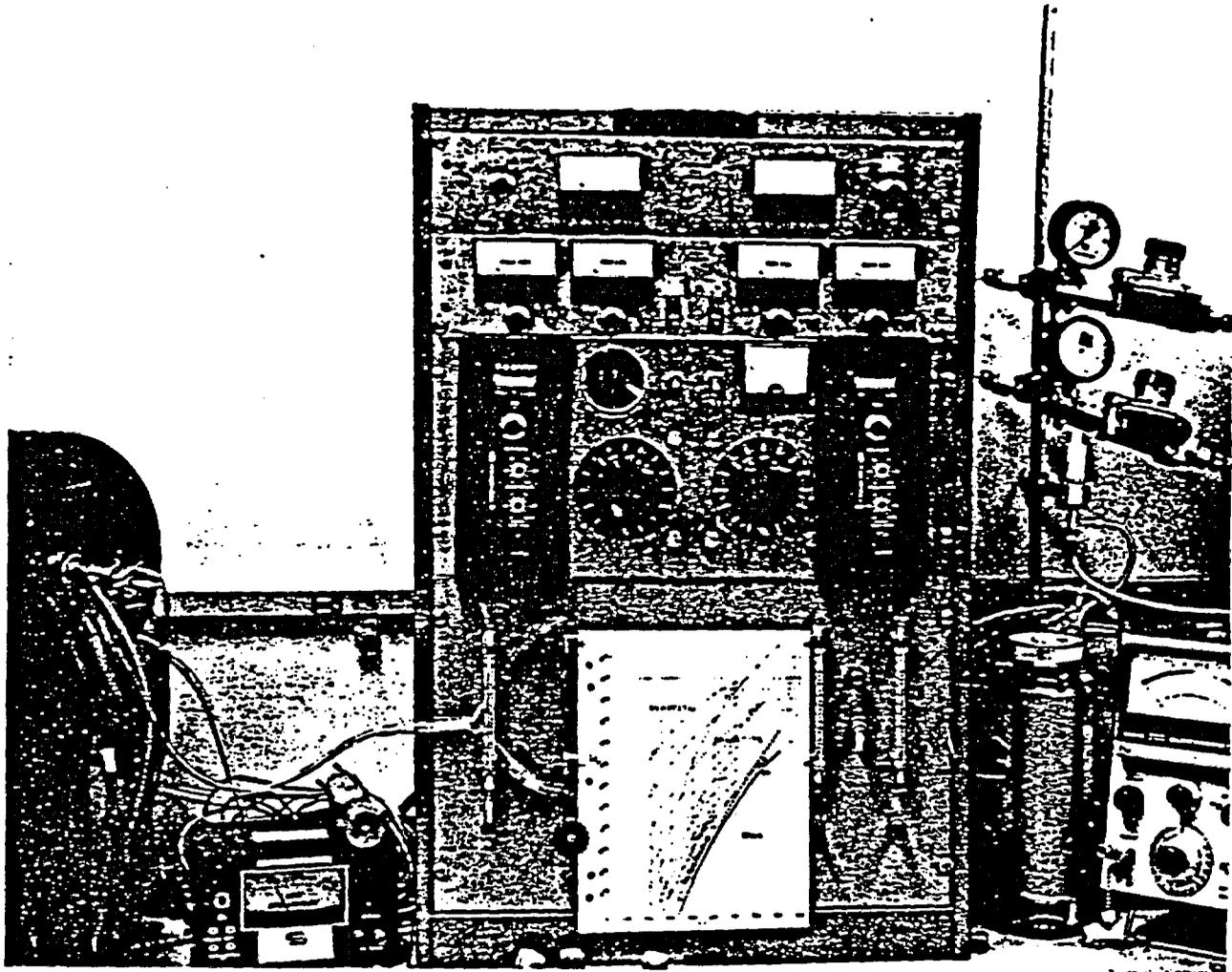


Figure 47.—Single-sample furnace used for paleointensity determinations and thermal demagnetization in controlled atmosphere.

ity Index²) is based on the tightest grouping of directions. It is calculated for all possible combinations of three or more successive directions during demagnetization; that is,

$$S.I. = \max (\text{Range}^2 / \sigma_{63}).$$

S.I. can estimate the range over which a single component of remanence can be isolated.

When analyzing susceptibility, and remanence for comparing different rock units, it is best to determine their log-normal distribution rather than their mean values of remanence or

susceptibility. This procedure is recommended because of the generally extreme variations in amplitude within units. The logarithms of the values tend to have a symmetrical (gaussian) distribution, suggesting that the main influence on both susceptibility and intensity within any rock unit is the distribution of grain size.

For computation purposes, the rock-magnetism laboratory has all of the computations for pole positions D and I and Fisher statistics programmed on a hand calculator that has printer output.

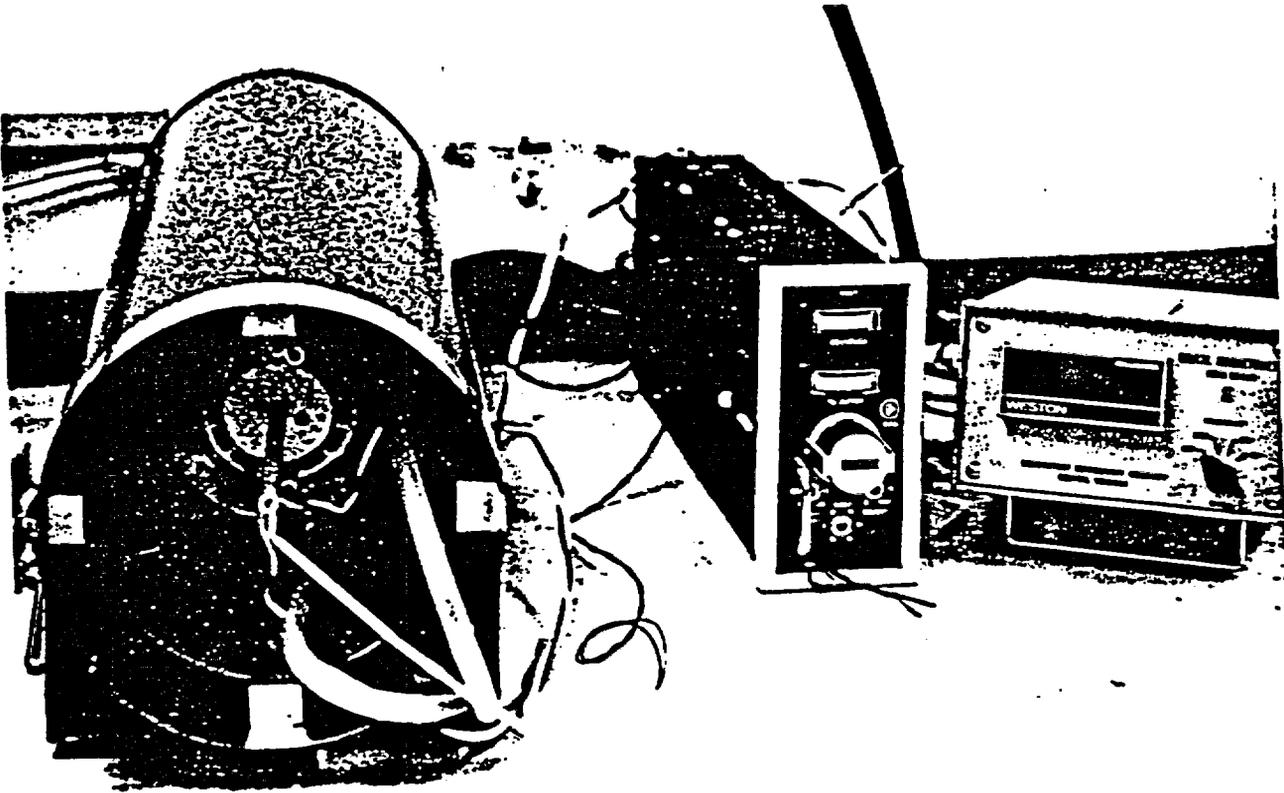


Figure 48.--Multisample thermal demagnetization system shown with calibration magnetometer.

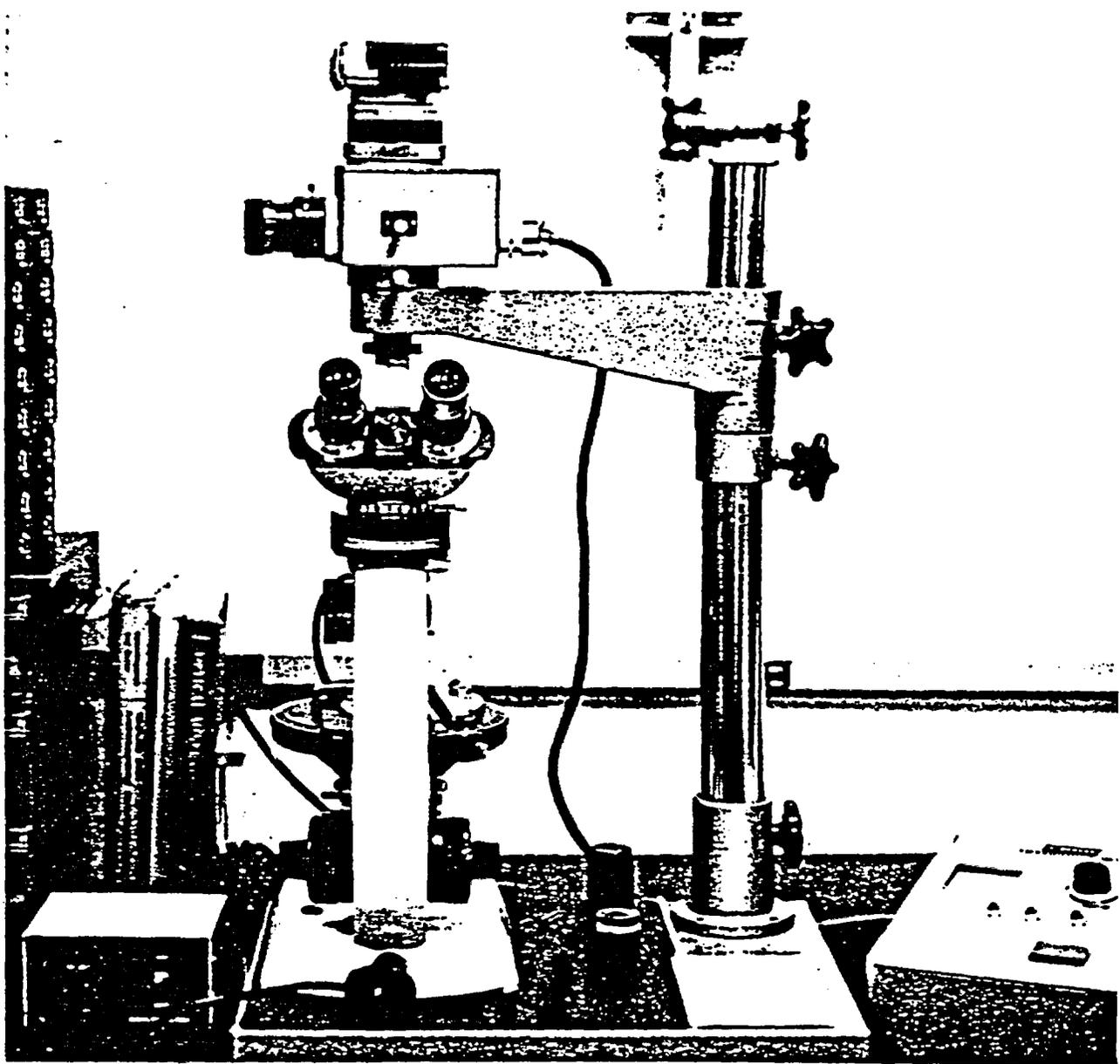


Figure 49.—Petrographic microscope with automatic camera attachment.

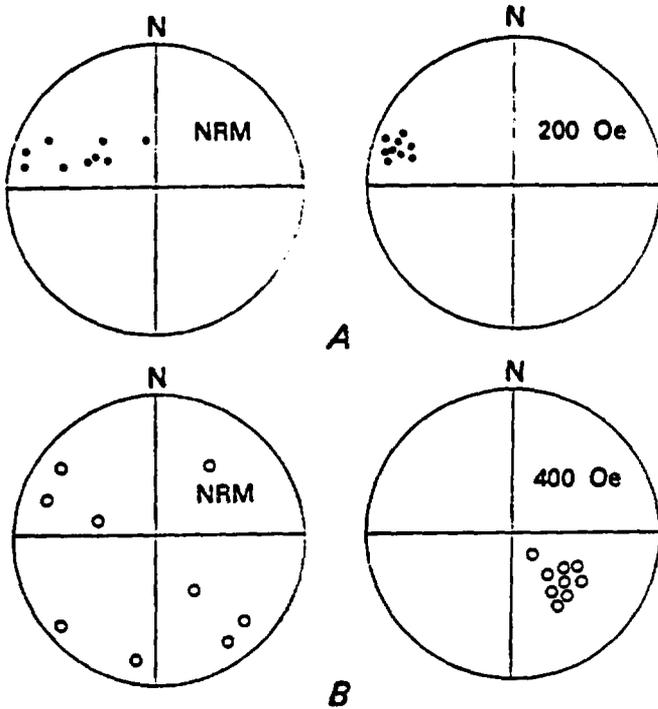


Figure 50.--Effects of alternating-current demagnetization. A, VRM (viscous remanent magnetization); B, IRM (isothermal remanent magnetization).

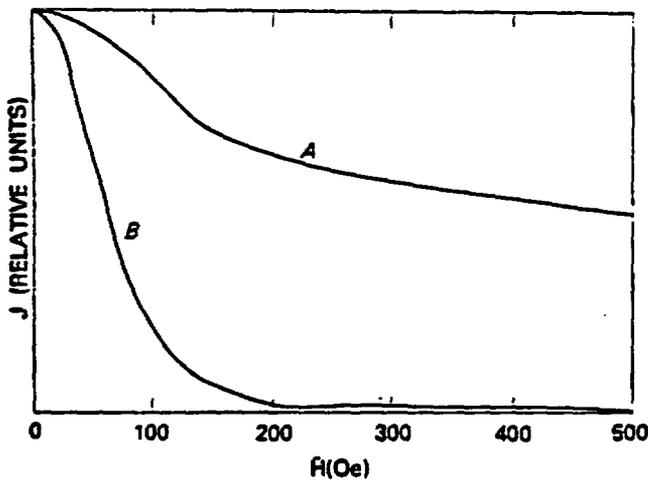


Figure 51.--Decay of magnetic intensity (J) of sample under influence of alternating field (H_{Oe}). A, VRM (viscous remanent magnetization) and B, IRM (isothermal remanent magnetization).

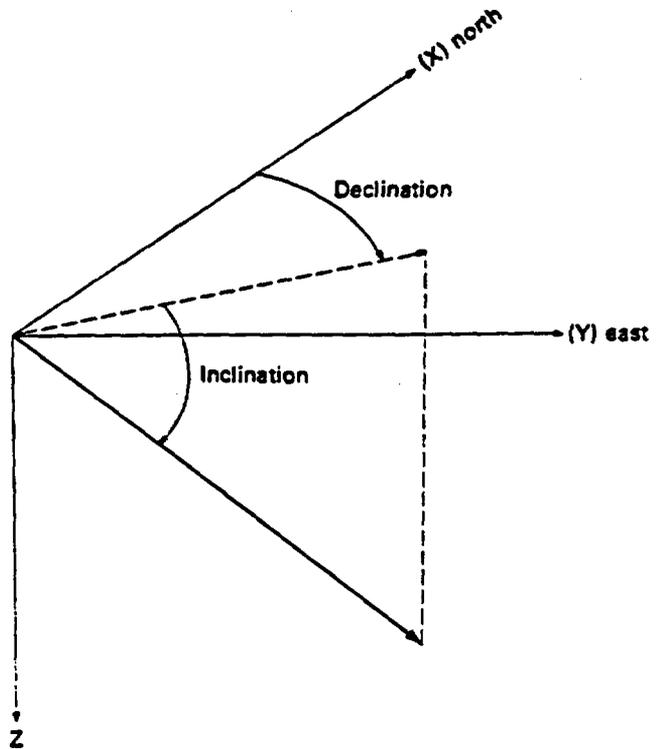


Figure 52.--Components of magnetization in a rock.

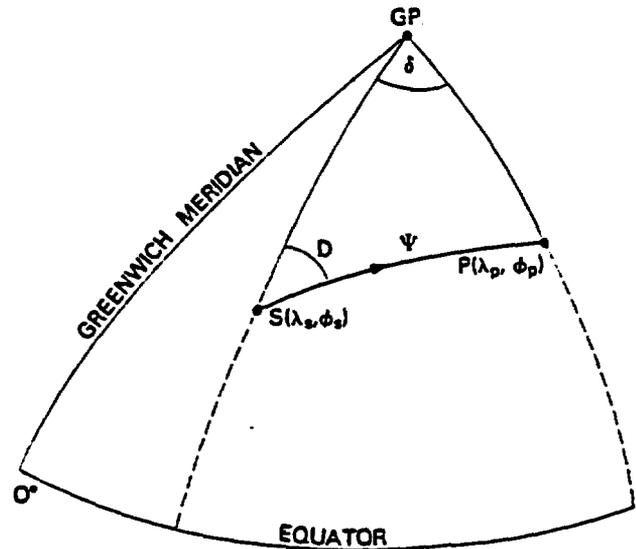
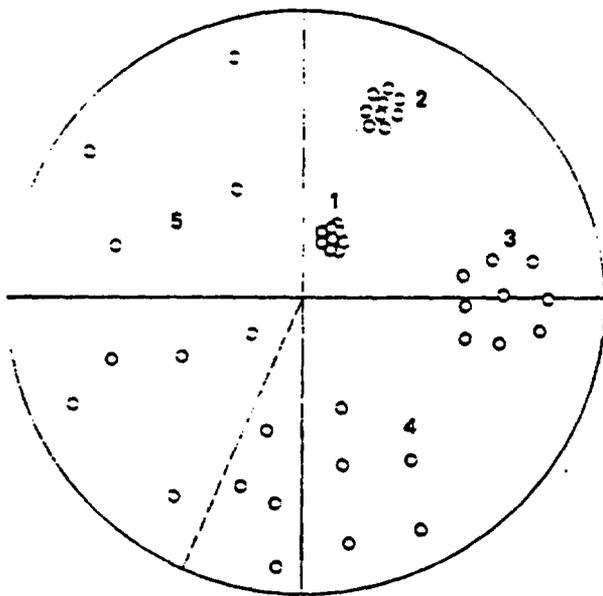


Figure 53.--Pole-position representation of resultant magnetization in a rock referenced to geomagnetic coordinates where S is sample location, D is declination, P is the geographic location of the paleomagnetic pole, and ψ is the distance to the pole from the sampling site.



GROUP	R	K	α_{95}	θ_{63}
1	8.99	906	1.7	2.7
2	8.97	347	2.8	4.4
3	8.74	32	9.2	14.4
4	8.24	10.6	16.6	25.1
5	7.11	4.2	28.4	40.0

Figure 54.--Standard paleomagnetic statistical parameters. R, resultant vector sum; K, precision parameter; α_{95} , circle of confidence; and θ_{63} , circular standard deviation.

REFERENCES CITED

- Banerjee, S. K., and Hargraves, R. B., 1971, Natural remanent magnetization of carbonaceous chondrites: *Earth and Planetary Sci. Letters*, v. 10, p. 392.
- Fisher, R. A., 1953, Dispersion on a sphere: *Royal Soc. Proc., A*, v. 217, p. 295-305.
- Helsley, C. E., and Shoemaker, E. M., 1973, Magnetostratigraphy of the Moenkopi Formation: *Geol. Soc. America Abs. with Programs*, v. 5, no. 7, p. 665-666.
- Herndon, J. M., Rowe, M. W., Larson, E. E., and Watson, D. E., 1975, Magnetism of meteorites--A review of Russian studies: *Meteorites*, v. 7, p. 263-284.
- Larson, E. E., and Walker, T. R., 1975, Development of CRM during early stages of red bed formation in Late Cenozoic sediments, Baja, California: *Geol. Soc. America Bull.*, v. 86, p. 639-650.
- Sato, M., 1970, An electrochemical method of oxygen fugacity control of furnace atmosphere for mineral synthesis: *Am. Mineralogist*, v. 55, p. 1424-1431.

- Stacey, F. D., Lovering, J. F., and Parry, L. G., 1961, Thermomagnetic properties, natural magnetic moments and magnetic anisotropies of some chondritic meteorites: *Jour. Geophys. Research*, v. 66, p. 1523.
- Theilner, E., and Theilner, O., 1959, Sur l'intensité du champ magnétique terrestre dans le passé historique et géologique: *Annales Géophysique*, v. 15, p. 285-376.
- Watson, D. E., Larson, E. E., Herndon, J. M., and Rowe, M. W., 1975, Thermomagnetic analysis of meteorites, 2--C2 chondrites: *Earth and Planetary Sci. Letters*, v. 27, p. 101-107.

SPECTROSCOPIC PROPERTIES

By Graham R. Hunt

Introduction

Spectroscopy may be defined very broadly as the study of the interaction of electromagnetic radiation with matter; and a spectrum, as a plot of the intensity of the transmitted, reflected, or emitted radiation as a function of its energy, frequency, or wavelength.

The electromagnetic spectrum extends from the high-energy (short-wavelength) cosmic-ray region to the low-energy (long-wavelength) domain that is well below audio frequencies. Of this vast wavelength range, extending from less than 10^{-8} μm to more than 10^{10} μm , only the region from the NUV (near ultraviolet) to the FIR (far infrared) (from 0.18 to 50 μm) is currently investigated in the spectroscopy section of the Petrophysics Laboratory. A much greater range (covering 15 orders of magnitude) at longer wavelengths is covered in the section entitled "Electrical Properties." Even though the NUV-FIR range is comparatively small, it is the principal region in which electromagnetic radiation truly interacts with virtually all matter, without at the same time disrupting it. Because it is also the range in which energy sources and detection systems are well developed and in which atmospheric effects do not completely remove all solar radiation, it is the prime range over which remote sensing techniques are traditionally applied.

Figure 55 shows the electromagnetic spectrum and some of the more common ways in which the energy, frequency, or wavelength can be expressed. These relationships can be simply expressed (using consistent units) as

$$v = \frac{c}{\lambda}$$

where v is the frequency, λ , the wavelength, and c , the speed of light; and as

$$e = hv = \frac{hc}{\lambda}$$

where e is the energy and h , Planck's constant.