

**DENSITY, MAGNETIC SUSCEPTIBILITY, AND NATURAL REMANENT
MAGNETIZATION OF ROCKS IN MINNESOTA: AN MGS ROCK PROPERTIES
DATABASE**

Val W. Chandler and R. S. Lively

**A Final Report for Sponsored Project B37919
Minnesota Minerals Coordinating Committee, and
Division of Minerals, Minnesota Department of Natural Resources**

Minnesota Geological Survey

June 30, 2011

VERSION 2.0

Rock property data can be viewed and obtained by going to the Minnesota Geological Survey home page and following the link to online services.

Every reasonable effort has been made to ensure the accuracy of the factual data on which this compilation is based; however, the Minnesota Geological Survey does not warrant or guarantee that there are no errors. Users may wish to verify critical information; sources include both the references listed here and information on file at the offices of the Minnesota Geological Survey in St. Paul. No claim is made that the data as shown are rigorously correct, however, and it should not be used to guide engineering-scale decisions without site-specific verification.

INTRODUCTION

Geologic interpretation of gravity and magnetic anomaly data in a given area is greatly enhanced if density, magnetic susceptibility (MS) and natural remanent magnetization (NRM) data are available for representative rock-types (Chandler and others, 2008). Along with geologic information from outcrop and drill-holes, rock property data help relate geophysical anomaly signatures to probable rock types, and provide constraints on the use of anomaly data as a tool for mapping and for modeling geology at depth. Rock property data are particularly important to Minnesota where Precambrian rocks, which comprise the bulk of the bedrock surface, are associated with a wide range of density, MS and NRM values and are mostly under a thick cover of unconsolidated glacial sediments.

In 2003, the MGS released a rock properties database with 4121 entries that included 2544 densities, 3755 magnetic susceptibility measurements, and 347 NRM values. This data proved useful for both geologic mapping and mineral exploration, but was seriously limited in several respects. Perhaps most seriously, the database was designed for individual determinations referenced to a surface location, with no provision for specifying elevation or depth. As a result it did not contain any data logs from core or down-hole sampling. Vertically referenced rock property data is available and should be incorporated into the database in a consistent format. In addition, several major geologic units in Minnesota were under-represented in 2003; for example, only 62 samples of Paleozoic rocks, one sample of Cretaceous rocks, and no Quaternary deposits had density information. Although these materials can be ignored as “overburden” in some studies of Precambrian rocks and crustal structure, they can be germane to engineering and environmental studies, such as depth to bedrock.

A project was initiated in 2009 to upgrade the rock properties database by providing a format that could incorporate vertically-referenced samples from drill core, add readily available density and magnetic susceptibility data from core into the database, and allow a straightforward addition of core log data in the future. We also incorporated new, single point, surface-referenced data (measurements from discrete outcrop and single core and hand samples without depth information) that were acquired during MGS projects since 2003. Some data was also recovered from older projects that had been missed by the earlier compilation.

The current database consists of location 9,032 entries (Figure 1). The surface-based, point data include 5,272, 6,939, and 903 density, magnetic susceptibility, and NRM measurements, respectively. Down-hole data from 146 drillcore have also been incorporated, yielding an additional 1,145 and 9,622 measurements of density and magnetic susceptibility, respectively. Finally, the location of new and some pre-existing rock property sites was improved by using outcrop polygons and improved base-map overlays to adjust point locations to most-likely positions as necessary. Thus, the revised database represents a significant improvement in size, types of material, and quality, and should serve the needs of the MGS and the broader geologic community for many years to come.

HISTORY OF ROCK PROPERTY INVESTIGATIONS IN MINNESOTA

The first systematic efforts to acquire rock property data in Minnesota began in the early 1950's. Bleifuss (1952) and Mooney and Bleifuss (1953) collected and published magnetic susceptibility and density data from a variety of Precambrian rocks throughout the state. At about the same time the U. S. Geological Survey began acquiring magnetic susceptibility and NRM data in east-central and northeastern Minnesota. Some of these data were published in papers by Bath (1962), Jahren (1965), and Sims (1972). Paleomagnetic studies of the Midcontinent Rift in Minnesota began in earnest during the 1960's, with work conducted under the auspices of the U. S. Geological Survey (Beck, 1970; Beck and

Lindsley, 1969; Books, 1972); The University of Western Ontario (Palmer, 1970); and the Geological Survey of Canada (Dubois, 1962). After the conclusion of these paleomagnetic investigations, little rock property data were collected for several years.

A resurgence of data acquisition of rock properties in Minnesota began in 1979 with the initiation of high-resolution, state-wide aeromagnetic program (Chandler, 1991) and the continuation of a gravity survey program that began in the 1960's (Chandler and Schaap, 1991). The rock properties program involved measurements of density, magnetic susceptibility, and NRM for various rock-types throughout the state, to support interpretation of the gravity and aeromagnetic data. This activity, mostly carried out between 1979 and 1984, involved field acquisition of new data and in-house measurements using samples at MGS. Since 1984, acquisition of rock property data has continued as part of a variety of state-funded and federally-funded drilling and mapping projects. As a general rule, rock property measurements are included in MGS projects where a significant part of the geologic mapping or investigation at depth involves gravity and magnetic interpretation.

HIGHLIGHTS OF THE 2009-2011 UPGRADE

Addition of Drill Core Data

The revised database includes 146 drill-hole locations with down-hole data at referenced depths listed in log descriptions of the core. From these, 1,145 samples have density data, 9,622 have magnetic susceptibility data, and 132 samples have both. The core dataset was derived from notebooks and other files at the MGS, drillcore information from partner agencies, and, in a few cases, new readings on core stored at either the MGS and Minnesota Department of Natural Resources (MNDNR). Priority was given to 94 magnetic susceptibility logs that were collected by Jahren in the 1950's (REF). This group of data only existed in an aging set of notebooks, and although some are from core still available at the MGS or the MNDNR, others are from Company cores and are no longer available. Furthermore, some of Jahren's core data were from the Cuyuna Iron Range, a region where the 2003 rock properties file was especially lacking. To supplement the Cuyuna magnetic susceptibility, new density data were collected from four Jahren cores that were still stored at MGS.

Additional density and MS data were added from several regions. Magnetic susceptibility logged by the Natural Resources Research Institute (NRRI) in the Babbitt area (Duluth Complex) and the Virginia Horn area (Archean greenstone-granite rocks) were incorporated, along with similar data acquired from some deep drill-holes in the Paleoproterozoic Animikie sequence along and south of south of the Mesabi Range. The core data also includes density measurements of Mesoproterozoic sedimentary rocks in the Midcontinent Rift and some MS measurements on core of Quaternary sediments acquired from rotary-sonic drilling.

Addition of New Surface-Referenced (X, Y) Data

Several projects since 2003 have produced a large backlog of rock property data from in-situ and hand samples. During the Deep Underground Scientific and Engineering Laboratory (DUSEL) evaluation for the University of Minnesota, rock property data were collected to facilitate interpretation of the gravity and magnetic detail in the Tower-Soudan area of NE Minnesota. NRRI measured 167 densities and 510 magnetic susceptibilities from its hand sample inventory, while the MGS compiled 428 density, 494 MS, and 329 NRM determinations. The latter compilation involved some new data collection, but consisted chiefly of results previously acquired by R. J. Ikola, G. D. Bath, C. E. Jahren, and V. W. Chandler during various projects. As part of U.S. Geological Survey STATEMAP work, 568 density and 925 MS determinations were acquired from lavas and intrusions along the North Shore of Lake Superior and 881 MS measurements were collected from the Vermilion Granitic Complex in the Crane Lake area of northeastern Minnesota. Separately, 129 density, 30 MS, and 96 NRM determinations were compiled from the Sioux Quartzite, which was underrepresented in the 2003 database.

Addition of Densities Inferred from Seismic Velocity Data

Density data for glacial deposits and most sedimentary rocks has generally been very limited in Minnesota. The problem exists because many of these materials are porous and poorly consolidated, making them unsuited for the classical density measurement technique a samples weight in air is compared to that in water. Knowing the density of these materials can be useful when applying the gravity method to determine thickness of unconsolidated deposits. Without this information the gravity method does not provide reliable information.

Several empirical relationships have been developed that estimate a sediment's density using P-wave velocities derived from seismic refraction surveys. The relationship derived by Gardner and others (1974) appears to be particularly useful for poorly-to-moderately consolidated sediments with P-wave velocities at or above 1.5 km/sec (Brocher, 2005; Chandler, 1994). The relationship is generalized as follows:

$$\rho(\text{g/cm}^3) = 1.74V_p^{0.25}$$

Where the P-wave velocity (V_p) is in km/sec.

Through the efforts of Mooney and others (1970), the MGS, and the Minnesota Department of Natural Resources, (<http://www.dnr.state.mn.us/maps/geophysics.html>) many seismic refraction surveys have been carried out in Minnesota and western Wisconsin over the past several decades, resulting in P-wave velocities which could be used in the above relationship. The results apply to several units under-represented in the 2003 database, including Keweenaw sedimentary rocks, Paleozoic sedimentary rocks, Cretaceous rocks, and saturated (sub-water table) glacial deposits. Un-saturated glacial materials near the surface were not included because a) the majority of glacial materials are saturated, and b) P-wave velocities for un-saturated sediments are substantially below the 1.5 km/sec threshold for the Gardner relationship. The results from this analysis produced 172 densities for Keweenaw sedimentary rocks, 176 densities for Paleozoic rocks, 9 densities for Cretaceous rocks, and 355 densities for saturated Quaternary deposits.

STRUCTURE OF THE UPGRADED DATABASE

Units:

Values of rock density, magnetic susceptibility and natural remanent magnetization (NRM) are given in SI units (Systeme Internationale, meter kilogram seconds), as opposed to the older c.g.s. units (centimeter, gram, seconds). Missing or no data cells are given a value of -999.

Conversions from SI units to cgs units can be made as follows:

Density-divide SI value by 1,000

Magnetic susceptibility-divide SI value by (4*pi)

NRM intensity-divide SI value by 1000

Use:

The rock properties dataset was created as part of a project file (mxd) in ArcGis 10, however, the specific shapefile and database tables that hold the data can be read by any version of ArcGis.

Coordinates of the data are NAD83, UTM, Zone 15.

The data are divided into four types: (1) sample, (2) drillcore, (3) seismic, and (4) site (Figure 1). For TYPE = Sample, a given property in the table represents either a single measurement or an average of several measurements taken from a hand sample or an in-situ measurement at an outcrop (magnetic susceptibility only). TYPE = Drillcore can either be a) based on a single measurement or an average of several measurements on a short segment of drillcore with reference to a surface position and no down-hole listing; or b) have multiple readings logged over a significant depth interval of core or cuttings. The field TYPE_MOD contains an attribute that indicates whether the drill-core is a single source or contains down-hole data. The latter are referenced to an X, Y position, like other entries in the database, but, in addition, are linked to a separate data file that includes the down-hole rock property measurements and their corresponding depth (DEPTH_FT). For inclined holes the depth refers to distance along core from the surface. The relate field from the point location file to the down-hole data files is RELATEID which is unique, while the SAMPLEID field indicates the drill-hole and is not unique. TYPE = Seismic refers to densities calculated from seismic velocity (V_p) data, obtained from seismic refraction surveys. This empirical approach estimates the density for poorly consolidated materials that are otherwise very difficult to determine. TYPE = Site indicates an average of measurements from multiple samples (see NUM_SAM) taken over a fairly large site, usually a quarry or large outcrop. Site data typically include paleomagnetic studies where sample-type data are no longer available, although some site-averaged densities by Fogelson (1956) have also been included.

Location Accuracy

The user must be always mindful of potential errors in location as well as map positional accuracy, especially for data that were acquired prior to 1960. In general, data acquired before 1960 are located on the basis of field notes, and are generally thought to be within 200-400 meters (1/8-1/4 mile) of their true position. Some older locations, however, have a location described only to a quarter section; this is especially true of old exploration holes, such as those logged by Jahren. For these situations, the point is placed at the center of the quarter section, and if the quarter section designation is correct, the sample should be within 570 meters (~1/3 mile) of its true position. Locations that are thought to be in error of 400 meters or more are annotated in either the COMMENTS or COMMENT2 field. Rock property data acquired after 1960, when high-quality topographic maps were becoming widely available, are generally thought to be located to an accuracy of 50-200 meters. Where available, outcrop locations were used as a reference to reposition some in-situ or hand sample points that appeared to be offset slightly from likely outcrops. Data locations acquired after the year 2000 are mostly based on GPS technology and are accurate to within about 30 meters.

Description of Database Parameters

RELATEID-This field contains a unique, sequential number for each entry within the database. The number is not correlative to specific sample types or data order. Its main function to provide a unique link to secondary data tables.

SAMPLEID – This field contains the sample or field number as assigned by the original collector. This is commonly alpha-numeric and is not consistent within the database. Although the same sample number could exist for different samples, it is not common.

TYPE – This field describes the type of sample used for this particular entry and can be as follows:

Sample - refers to measurements based on outcrop (in-situ) or a hand sample, single source

Drillcore – refers to measurements based on a discrete piece of core. May be single source with just an XY surface location or may also refer to secondary tables of density or magnetic susceptibility derived from subsurface intervals of core. Locations with secondary links are referenced in the TYPE_MOD field.

Site – contains properties based on average values of samples at a discrete site. Mainly used for paleomagnetic investigations where original sample-based data have been lost.

Seismic – contains density values estimated from seismic velocity data (V_p) using a relationship described by Gardner and others, (1974)

TYPE_MOD – contains a modifier to the TYPE field that allows the Drillcore sample type to be separated into those with down-hole data and those without (Down-hole samples). Entries with down-hole samples have a relate link that within an ArcGis environment will bring up one of two secondary tables with either down-hole density or magnetic susceptibility measurements and depth.

MAJOR_DIV – contains information about the geologic association of the sample on the scale of an orogen or subprovince (for example, Penokean orogen or Wawa subprovince)

MINOR_DIV – refers to a large map unit, usually a major geologic body or a rock formation. (for example, Ely Greenstone Belt or Giant's Range Batholith).

SUB_DIV – this parameter allows for further geologic division wherever necessary, usually refers to a local rock unit or body

ROCK_TYPE - a very general description of the sample as given by the collector, and does not conform to any particular rock classification scheme. Thus, a rock that is described as a "gabbro" by one collector may be described as a "troctolite" by another. Additional geologic information may be given in the COMMENT field (see below).

DENSITY_SI – gives density in SI units (kilograms/cubic meter).

Density was determined one of two different ways, as designated by TYPE.

For TYPE = Sample, the measurement was made using a Jolly spring balance. Density measurements were made using small chips approximately 2.5 cm. x 5 cm x 1.0 cm., or small cores about 2.5 cm in diameter and length. Measurement precision is about 10 SI units. Every reasonable attempt was made to ensure that the samples were unweathered, and porous samples (such as sandstone) were soaked in water prior to being measured to remove as much air as possible. However unsaturated pore space may have persisted in some samples, and if a density appears to be unusually low, it should be used with caution. For the site-based data the number of samples used to compute the average density is provided in NUM_SAM.

For TYPE = Seismic, the density determination is calculated from seismic velocity (V_p) as derived from seismic refraction data using the relationship described by Gardner and others (1974). All materials are assumed to be saturated.

MAG_SUS_SI - Magnetic susceptibility in SI units, based on measurements from a variety of instruments. Wherever appropriate, corrections have been made for estimated air space (chip samples)

and sample dimensions, in accordance with recommendations given by the manufacturers of a particular instrument. Most magnetic susceptibilities are precise to about 0.0001 SI units, although those acquired using the Scintrex device, as well as measurements by C. E. Jahren, G. D. Bath, and R. L. Bleifuss and H. M. Mooney (see citation field in database) can be as much as an order of magnitude less precise (see parameter MAG_SUS_LT below). For the site-based data the number of samples used to compute the average susceptibility is provided in the NUM_SAM field.

MAG_SUS_LT – Means magnetic susceptibility is less than the value given here. In other words the magnetic susceptibility is non-zero, but too weak to be properly determined by the device used. This attribute is included for older, less sensitive measurements, such as those by C. E. Jahren, G. D. Bath, and R. L. Bleifuss and H. M. Mooney.

CITATION - This category credits the individuals who acquired the data. If two names are given, the first designates who was responsible for field collection, and the second designates who did the laboratory measurements.

ACQ_DATE – Estimated date of acquisition, as available. If precise dates are not available, date is rounded off to nearest month or year. If rock properties were acquired either during or shortly after field work, this date usually refers the time of field collection, as derived from field notes. If, however the time of field collection is unknown, or is separated by many years from the time of property measurement, the date refers to the time of measurement. The latter situation is especially pertinent to magnetic susceptibility logging by Jahren, who used cores that were sometimes drilled decades before his study.

MAG_METHOD - This category describes the methodology and instrumentation used for magnetic susceptibility measurements. Many of the magnetic susceptibility measurements by MGS staff were made with a Bison model 3101A magnetic susceptibility meter, using one the following modes: (1) in-situ (outcrop) measurements using a 6-inch coil; (2) crushed hand samples in plastic vials using an internal coil; and (3) small cores using an internal coil. Other magnetic susceptibility measurements by MGS were made using a hand-held EDA Instruments Model K-2 magnetic susceptibility meter on core, hand sample, or outcrops. Because the K-2 meter samples a very small volume of rock, presented values are commonly based on the average of 3 to 10 individual readings. Some MGS measurements were made using a Scintrex model SM-5 magnetic susceptibility meter, which operated very much like the EDA instrument. Some of the more recent measurements at MGS and NRRI were made with a Kappameter. Laboratory measurements of magnetic susceptibility by C. E. Jahren, G. D. Bath, R. L. Bleifuss and H. M. Mooney (see citation field in database) were made using laboratory-built devices that were based on self-inductance in coils.

Where applicable, this field may also specify whether an astatic magnetometer or a spinner magnetometer was used for NRM measurements. For older studies these instruments were typically laboratory-built devices, such as those that were at the U. S. Geological Survey and the Geological Survey of Canada. Measurements of NRM without any specification in this field were made at MGS using a Schonstedt Model SSM-1 spinner magnetometer.

COMMENTS - This category provides supplemental information on a given sample. In some cases it presents additional geologic information, in others it provides more detail about the precision of the determination or its location.

NUM_SAM – This category describes the number of samples used, if known, for site-averaged parameters (TYPE = Site), such as might be necessary for paleomagnetic studies where sample-based measurements have been lost.

Note: The next three categories present NRM determinations. Where sample-based (TYPE = Sample) NRM data represent initial (raw) readings with no "cleaning" by either thermal or alternating field (AF) demagnetization. Therefore, the user must be cautious of the effects of lightning strikes and other spurious NRM components. Where site-based (TYPE = Site) the NRM data is commonly "cleaned" by either thermal or AF methods and information on this cleaning is provided in the comment field, where available

J_NRM – Intensity of NRM in SI units (**ampere-m²/m³**).

DEC_NRM – Declination of NRM (degrees).

INC_NRM- Inclination of NRM (degrees).

POLARITY - gives the NRM polarity as N (normal or downward directed) or R (reversed or upward directed), and is given where no other NRM data are available.

GEO_STRIKE – Strike of structural correction applied to the NRM data. If blank, no structural correction has been applied.

GEO_DIP - Dip of structural correction applied to the NRM data. If blank, no structural correction has been applied.

TIME_DIV – Gross time division of rock unit, as inferred by geo-referencing point locations to S21, the published state bedrock map of Minnesota (Jirsa and others, 2011)

POINT_X – UTM easting (meters) NAD83, Zone 15N

POINT_Y - UTM northing (meters) NAD83, Zone 15N

S_ELEV_FT – Surface elevation, in feet relative to mean sea level. Inferred from the 30 meter DEM grid of the U. S. Geological Survey. Values of -999 indicate points outside of the boundary of the Minnesota DEM

COMMENT2 – Additional comments, if needed

Drill-hole Parameters (Core and Cuttings Logs)

These files are linked to the main rock properties database by the RELATEID attribute. The relate is pre-built to connect the point location file with both of the secondary tables, one containing down-hole density data and the other down-hole magnetic susceptibility data. The connection functions only within the ArcGIS environment. It operates by selecting a point or points in the location table then using the related tables functionality of the attribute table to open the secondary tables. The attributes are the same as described for the rock properties database, but a new parameter DEPTH_FT was added to indicate the

depth of a particular measurement. In the case of inclined holes, DEPTH_FT refers to the distance along the core from the surface, not the true depth. In most cases DEPTH_FT refers to the actual depth of the measurement, but some of Jahren's logs consisted of multiple readings over 5 foot intervals. In these situations the average values over the interval was used, and DEPTH_FT was assigned a value at the middle of the 5 foot interval.

ACKNOWLEDGEMENTS

Acquisition of data in the 1950's was funded by the University of Minnesota and the U. S. Geological Survey. Acquisition from 1979 to 1984 was supported by the Aeromagnetic Survey Program of the Minnesota Geological Survey, which was funded by the Minnesota Legislature as recommended by the Legislative Commission on Minnesota Resources. Additional legislative support was provided through the Minerals Coordinating Committee and the State Special Appropriation for the Minnesota Geological Survey. Support since 1984 has been provided through the U. S. Geological Survey (COGEOMAP and STATEMAP projects), and the MGS-MNDNR County Geologic Atlas Program. Finally, the legislative support for this upgrade as recommended by the Minnesota Mineral Coordinating Committee and managed through MNDNR is greatly appreciated.

Many individuals have contributed to the rock properties database over the years. Charles Jahren generously provided the notes, data, and samples that he and Gordon Bath used in their studies during the 1950's. Professors Myrl E. Beck, Jr. (Western Washington University) and H. Currie Palmer (The University of Western Ontario) generously provided field materials and other information from their own studies. Professor John C. Green (University of Minnesota, Duluth) provided unpublished paleomagnetic data from studies by Kenneth G. Books and others. In addition to those individuals named in the CITATION category within the database, others who have assisted at various times with the MGS data include, Laura Beauchane, Terri Haake, Lisa Kivaekas, Angela McGowan, Peter McSwiggen, Sahu Sanghamitra, Bryan Schaap and Dale Setterholm. During the summer of 2010 Roger Morrison lent valuable assistance during the early stages this compilation. Finally, the authors wish to give a special thanks to Jack Barland who worked on the project as a student during 2010-2011. Jack's efforts spanned data acquisition through GIS compilation, and his skills as a quick learner and a diligently consistent worker added much to the success of the program.

References Cited

Bath, G. D., 1962, Magnetic anomalies and magnetizations of the Biwabik Iron Formation, Mesabi Area, Minnesota: *Geophysics*, v. 27, number 5, p. 627-650.

Beck, M. E., 1970, Paleomagnetism of Keweenaw intrusive rocks, Minnesota, *Journal of Geophysical Research*, v. 75, p. 4985-4996.

Beck, M. E., and Lindsley, N. C., 1969, Paleomagnetism of the Beaver Bay Complex, Minnesota: *Journal of Geophysical Research*, v. 74, p. 2002-2013.

Bleifuss, R. L., 1952, Correlation of magnetite content with magnetic susceptibility measurements of Minnesota Precambrian rocks: University of Minnesota, M.S. thesis, 46 p.

Books, K. G., 1972, Paleomagnetism of some Lake Superior Keweenawan rocks: U. S. Geological Survey Professional Paper 760, 42 p.

Brocher, T. M., 2005, Compressional and Shear Wave Velocity Versus Depth in the San Francisco Bay Area, California: Rules for USGS Bay Area Velocity Model 05.0.0, U. S. Geological Survey Open-File Report 05-13172005

Chandler, V.W., 1994, Gravity Investigation for Potential Ground-Water Resources in Rock County, Minnesota, Minnesota Geological Survey, Report of Investigations, RI-44, 24 p.

Chandler, V. W., 1991, Aeromagnetic anomaly map of Minnesota: Minnesota Geological Survey, State Map Series, S-17, Scale 1:500,000.

Chandler, V. W., and Schaap, B. D., 1991, Bouguer gravity anomaly map of Minnesota: Minnesota Geological Survey, State Map Series, S-18, Scale 1:500,000.

Chandler, V.W., Jirsa, M.A., and Boerboom, T.J., 2008, A gravity and magnetic investigation of east-central Minnesota: Insights into the structure and evolution of the Paleoproterozoic Penokean Orogen, Minnesota Geological Survey, Report of Investigations, RI-66, 33 p.

DuBois, P. M., 1962, Paleomagnetism and correlation of Keweenawan rocks: Geological Survey of Canada Bulletin 71, 75 p.

Fogelson, D. E., 1956, A gravity survey of Redwood County, Minnesota, University of Minnesota, unpublished M.S. thesis, 40 p.

Grout, Frank F. and Wolff, J. F. Sr., 1955, The geology of the Cuyuna District, Minnesota, A progress report, Minnesota Geological Survey, Bulletin 36, 144 p.

Gardner, G. H. F., Gardner L. W., and Gregory, A. R., 1974, Formation velocity and density—the diagnostic basics for stratigraphic traps, *Geophysics* **39**, p. 770-780.

Jahren, C. E., 1965, Magnetization of Keweenawan rocks near Duluth, Minnesota, *Geophysics*, v. 30, p. 858-874.

Jirsa, M. A., Boerboom, T. J., Chandler, V. W., Mossler, J. H., Runkel, A. C., and Setterholm, D. R., 2011, Geologic map of Minnesota, Bedrock Geology, Minnesota Geological Survey, State Map Series, S-21, Scale 1:500,000.

Mooney H.M. and Bleifuss, R. L. 1953, Magnetic susceptibility measurements in Minnesota-Part 3, analysis of field results. *Geophysics*, v. 18, p. 383-393.

Mooney, H.M., Farnham, P.R., Johnson, S.H., Wolz, G. and Craddock, C., 1970, Seismic Studies Over the Midcontinent Gravity High in Minnesota and Northwestern Wisconsin, Minnesota Geological Survey, Report of Investigations, RI-11, 191 p.

Palmer, H. C., 1970, Paleomagnetism and correlation of some middle Keweenawan rocks, Lake Superior, *Canadian Journal of Earth Sciences*, v. 7, p. 1410-1436.

CAPTION

Figure 1. Rock property database - 2011: Point locations superimposed on the 2011 bedrock geology map of Minnesota. Dots colored by sample type. For explanation of geologic units see Jirsa and others (2011)

