MINNESOTA GEOLOGICAL SURVEY
INFORMATION CIRCULAR 35

GEOPHYSICAL SOLUTIONS TO GEOLOGIC PROBLEMS OF CONTINENTAL INTERIORS: A MINNESOTA WORKSHOP

UNIVERSITY OF MINNESOTA

Minnesota Geological Survey
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By

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PREFACE

Geophysics has long been a companion to geologic studies in Minnesota, where most of the bedrock lies beneath a thick cover of glacial drift. In 1979 the Minnesota Geological Survey (MGS), through funding by the Legislative Commission on Minnesota Resources (LCMR), began an ambitious geophysical project—a state-wide program of high-resolution aeromagnetic surveying. On the occasion of the completion of this highly successful program, the MGS through LCMR support hosted an international geophysics workshop during March 3-6, 1991.

The main objective of the workshop was to determine how the LCMR data and other geophysical information can most effectively be used, and what sorts of new geophysical investigations are desirable for Minnesota. Such an assessment must address private, academic, and governmental needs and must consider a diversity of topics, including mineral exploration, environmental and ground-water studies, geologic mapping, and crustal studies. The recommended tasks must also be consistent with the MGS mission of geologic mapping and framework studies.

Co-conveners were William J. Hinze of Purdue University, independent consultant Rodney J. Ikola, and Bruce D. Smith of the U.S. Geological Survey. Sessions were centered on near-surface studies, geologic mapping, mineral exploration, and crustal studies. Speakers were selected from diverse perspectives and included individuals from the United States, Canada, Australia, and Finland. Posters included presentations by some of the speakers, as well as other geophysicists working in the region. The workshop attracted over 100 earth scientists, representing 10 states and 4 countries, and the sessions stimulated many useful discussions and ideas.

This report summarizes the workshop, and discusses some of its most important recommendations. These recommendations will help set the course for Minnesota geophysics into the 21st century.

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INTRODUCTION: MINNESOTA GEOPHYSICS AT THE CROSSROADS

The opening session briefed workshop participants on the mission of the Minnesota Geological Survey and the importance of geophysics to that mission. The following paragraphs summarize some of the major points made by presenters Priscilla Grew, Matt Walton, and G.B. Morey (see program in Appendix A).

Geophysics and the geologic mapping mission of the Minnesota Geological Survey

The mission of the Minnesota Geological Survey (MGS) is to undertake the scientific study of the geology, mineral resources, and ground water for the state of Minnesota, and to uphold the land grant duties of the University of Minnesota, which are research, service, and teaching. The broad scientific objectives and the non-regulatory function of the MGS set it apart from the Minnesota Department of Natural Resources (DNR), the Minnesota Pollution Control Agency (PCA) and the Minnesota Department of Health (MDH), which are involved in various ways in regulating, managing, and protecting Minnesota's mineral and water resources. The broad scientific objectives of the MGS also differ from other agencies within the University of Minnesota, such as the Mineral Resources Research Center (MRRC) and the Natural Resources Research Institute (NRRI), whose research is focused on projects of economic interest. Central to the objectives of the Minnesota Geological Survey is the geologic mapping of both bedrock and unconsolidated materials.

The challenges to geologic mapping in Minnesota are enormous. The bedrock, which records various stages of crustal evolution spanning about 3.5 billion years of earth history, is almost completely covered by a complex and commonly thick sequence of glacial deposits. Because drill holes that penetrate the entire till sequence are sparse in many parts of the state, neither the till sequence nor the bedrock is well understood. Adding to the challenge is an urgent need for geologic mapping in many places where urban expansion is placing increasing demands on natural resources, and risks to them, as well. In these times of budget restrictions the only way to increase productivity is to work smarter, and geophysics is the key.

Geophysics has long been used by geologists working in Minnesota. In fact, the Cuyuna iron range, which was discovered in 1904 by dip needle, was the first iron ore district in the United States that was discovered wholly by a geophysical method. The first large-scale geophysical project in Minnesota was after WWII, when George M. Schwartz (then director of the MGS) made a co-operative arrangement with the U.S. Geological Survey (USGS) for surveying in Minnesota using the newly developed aeromagnetic method. The usefulness of the new method in mapping Precambrian geology beneath glacial drift was quickly realized and by 1950 over 40,000 square miles of northern Minnesota had been covered. During the 1960s while P.K. Sims was director of the MGS, the USGS aeromagnetic coverage over the entire state was completed, and a systematic gravity survey of the state began. P.K. Sims integrated aeromagnetic and gravity interpretation with geologic mapping, and produced a state geologic map in 1970, the first since 1932.

The LCMR-MGS aeromagnetic program

The origin and support of the Minnesota high-resolution aeromagnetic surveying program are credited to Professor Emeritus Matt Walton, director of the MGS from 1973 to 1986, and to the Legislative Commission on Minnesota Resources (LCMR) and its executive directors, Robert Hansen (from 1974 to 1988) and John Velin (since 1988). Impressed with the geophysical program of the Geological Survey of Finland, Walton organized an international workshop with LCMR support in 1978 to consider starting a geophysical program for Minnesota. The key recommendation of this workshop was a high-resolution aeromagnetic survey of the entire state. Although the regional-scale aeromagnetic coverage by the USGS had been useful for its time, the high-resolution program of the Geological Survey of Finland demonstrated that tremendous improvements were possible with modern technology and survey design. At the time, workshop participants saw the chief application of the program as mineral exploration, although they also realized that the program would greatly assist the MGS in its broad mission of geologic mapping and framework studies.

The high-resolution aeromagnetic surveying began in 1979, and was carried out continuously over 6 biennia (Fig. 1). In total the LCMR appropriated $4,475,000 for the program. The steadfast support of LCMR, without interruption or major budget reductions, was critical for maintaining quality control and productivity with a single project manager, Val Chandler, responsible for the 12-year effort. Additional aeromagnetic data have been contributed over north-central Minnesota by the USGS as part of the Conterminous United States Mineral Assessment Program (CUSMAP), and over southwestern Minnesota by USX Corporation (Fig. 1). In addition the Geological Survey of Canada (GSC) contributed the Minnesota portions of Lake of the Woods and Lake Superior (Fig. 1). A shaded-relief map of all aeromagnetic data is shown in Figure 2. The data are available in several forms, and essentially every company or individual involved in mineral exploration in the state has purchased products. In addition, public agencies involved in mineral studies have used the data as well, including DNR and NRRI. Most users prefer the aeromagnetic data in map form, but with advances in personal computers, more customers are acquiring the data in digital form, either as grid tapes or as recovered flight tapes.

Minnesota's geological framework and pertinent geophysical problems

MGS uses the aeromagnetic data chiefly for geologic mapping and framework studies of the Precambrian bedrock. The geologic map in Figure 3 is based in part on recent interpretations of the new aeromagnetic data. These data have revolutionized scientific understanding of Minnesota geology and have led to complete revisions in geologic interpretation of large areas of the state. Interpretation of the aeromagnetic data ranges from simple qualitative interpretation of contour maps to computer-based processing, which includes frequency domain filtering, Poisson analysis, and both forward and inverse modeling. Geologic interpretation is greatly strengthened by scientific test drilling, which has been

STATUS OF AEROMAGNETIC MAPPING

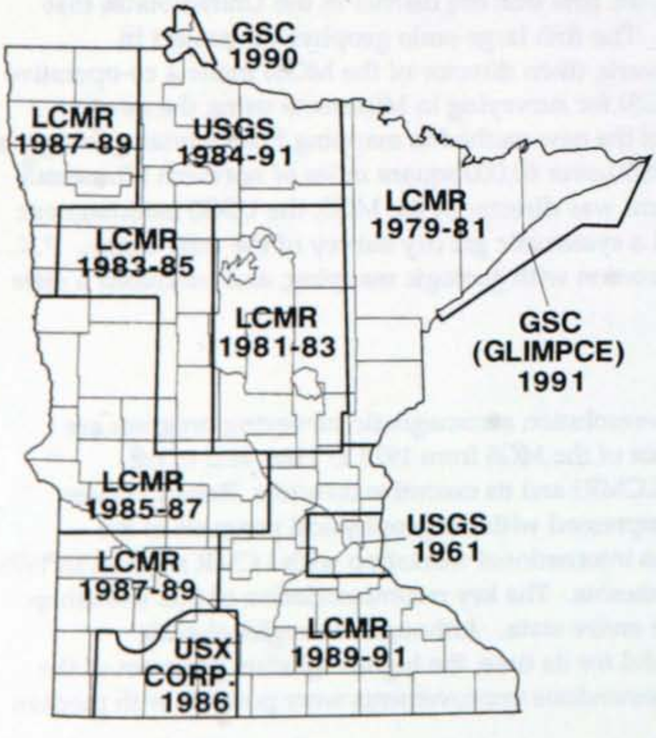

Figure 1. Summary of individual surveys of the aeromagnetic program. Dates on LCMR and USGS blocks refer to the time interval of individual surveys, whereas those on USX and GSC blocks refer to the year that the data were given to MGS. The USGS area in southeastern Minnesota is the Twin Cities Metropolitan Area where flight restrictions and cultural noise prevented new acquisition. In this area some low-resolution USGS data acquired 30 years ago were digitized and patched in.

supported in part by the LCMR aeromagnetic survey program. Interpretation can be further constrained by gravity data (average station coverage of 2-3 km state-wide) and by rock property data, both of which were also acquired in part through LCMR support.

The aeromagnetic data are already significant in geologic studies in Minnesota (Fig. 4). Qualitative interpretation as well as quantitative analysis of gravity and magnetic data have been used by the MGS to reinterpret the Penokean orogen (fold-and-thrust belt and Animikie basin on Fig. 3) in east-central Minnesota. Qualitative and quantitative analyses of aeromagnetic and gravity data have been used in recent mapping of the Archean greenstone-granite terrane in north-central Minnesota as part of the USGS CUSMAP program and for the MGS role in the Minnesota Minerals Diversification Program. The aeromagnetic data have also played a critical role in mapping the Kenora-Kabetogema dike swarm, which transects much of the greenstone-granite terrane in Minnesota (Figs. 3 and 4). In southwestern Minnesota, computer processing and model studies of aeromagnetic and gravity data, along with seismic studies by the University of Wyoming, are leading to a significant reinterpretation of the Archean gneiss terrane. In the Duluth Complex, derivative-enhanced aeromagnetic, and gravity data have been used in a geologic interpretation of the poorly exposed interior and, as part of the USGS COGEOMAP program, in detailed mapping along its southeastern margin. The aeromagnetic data have been combined with other geophysical data to investigate the crustal structure of the Midcontinent rift system in eastern Minnesota. The aeromagnetic data have even been useful in studying modern earthquakes in the state; these rare and generally weak tremors may be related to gentle reactivation of ancient faults that can be recognized in the aeromagnetic data (compare Figs. 2 and 3). Publications that either were produced through LCMR support or that used the LCMR data are listed in Appendix C.

Upon completion of the aeromagnetic surveying program, the LCMR supported this international workshop to assist MGS in preparing to use the new data base in the future. Workshop participants were requested to address the questions: How can Minnesota derive maximum benefit from its aeromagnetic and gravity data, and what new ways can MGS make these data available to outside users? What sort of new geophysical data should MGS acquire that would help in its mission and serve a broad base of interests?

STARTING AT THE TOP:
GEOPHYSICS IN THE INVESTIGATION OF NEAR-SURFACE GEOLOGY

In the 12 years since the aeromagnetic program began, a revolution has occurred in the application of geophysics to near-surface geology. Many geophysical methods originally developed for mineral and oil exploration have been redesigned to address problems of hydrology and surficial geology. Perhaps one of the most dramatic developments has been near-surface seismic reflection (Steeples, this volume). Seismic and other methods have already been successfully applied to both ground-water and near-surface investigations in Minnesota (Petersen, this volume), and more extensive use of them is clearly warranted. A workshop session was thus devoted to the application of geophysics to near-surface geology. The speakers were Don Steeples of the Kansas Geological Survey, Todd Peterson of the Minnesota Department of Natural Resources, Robert Thill of the U.S. Bureau of Mines, and Philip Davis of Geosphere Midwest, Inc. (See program in Appendix A and abstracts in Appendix B.) G.B. Morey and Dale Setterholm of the MGS participated in the panel discussion.

Many geologists and geophysicists working in Minnesota would like to make greater use of geophysics to determine depth to bedrock. Data on bedrock topography and the thickness of the overlying Quaternary sequence are of crucial importance to ground-water studies in the state (Petersen, this volume). Improving the state-wide data base on bedrock depths would benefit both public and private organizations involved in ground water and near-surface studies (Davis, this volume), and as noted by Norman Paterson during the panel discussion, could be of tremendous help in mineral exploration. Depth-to-bedrock studies on a regional scale are certainly consistent with the MGS

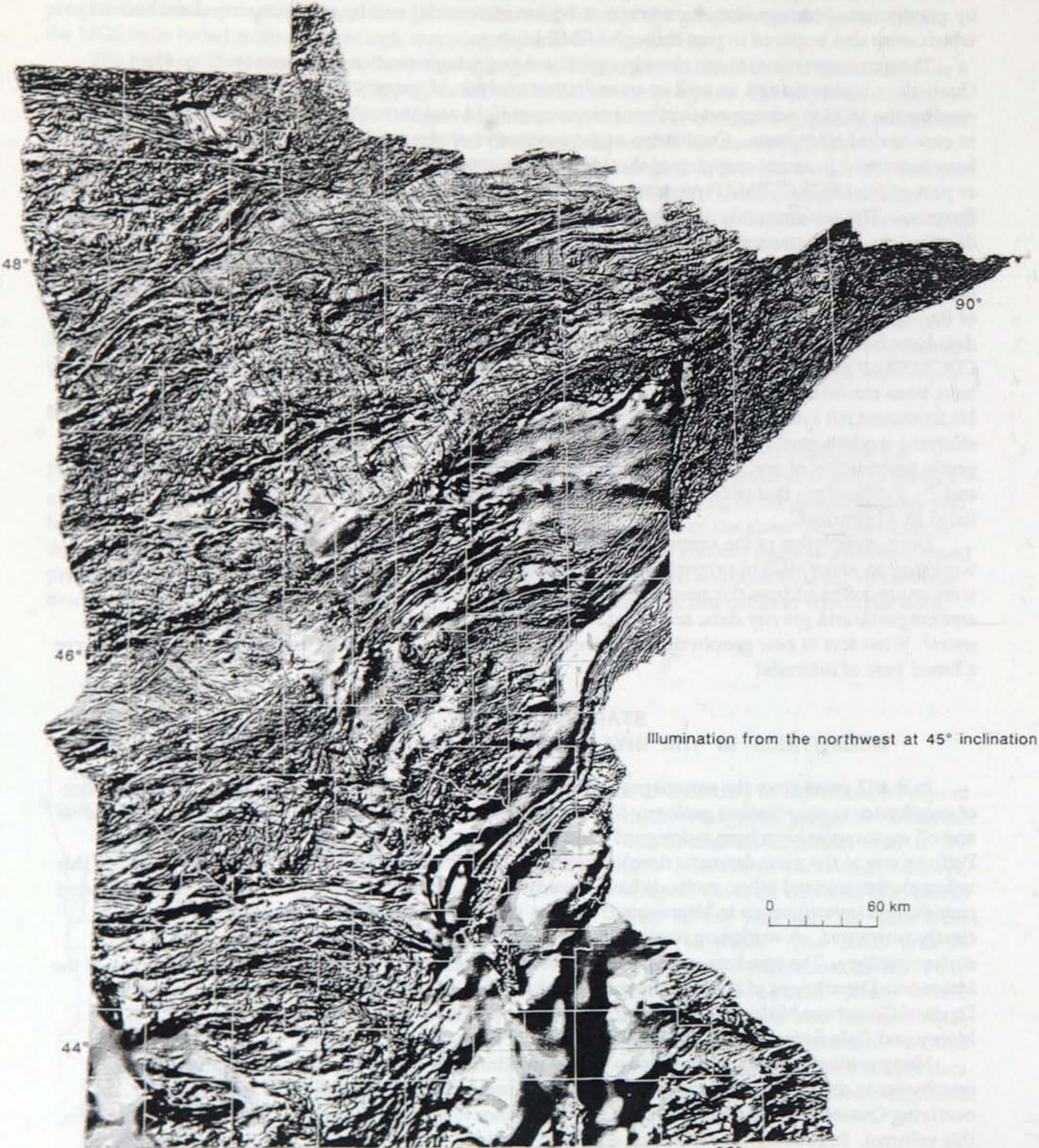

Figure 2. Shaded-relief aeromagnetic map of Minnesota.

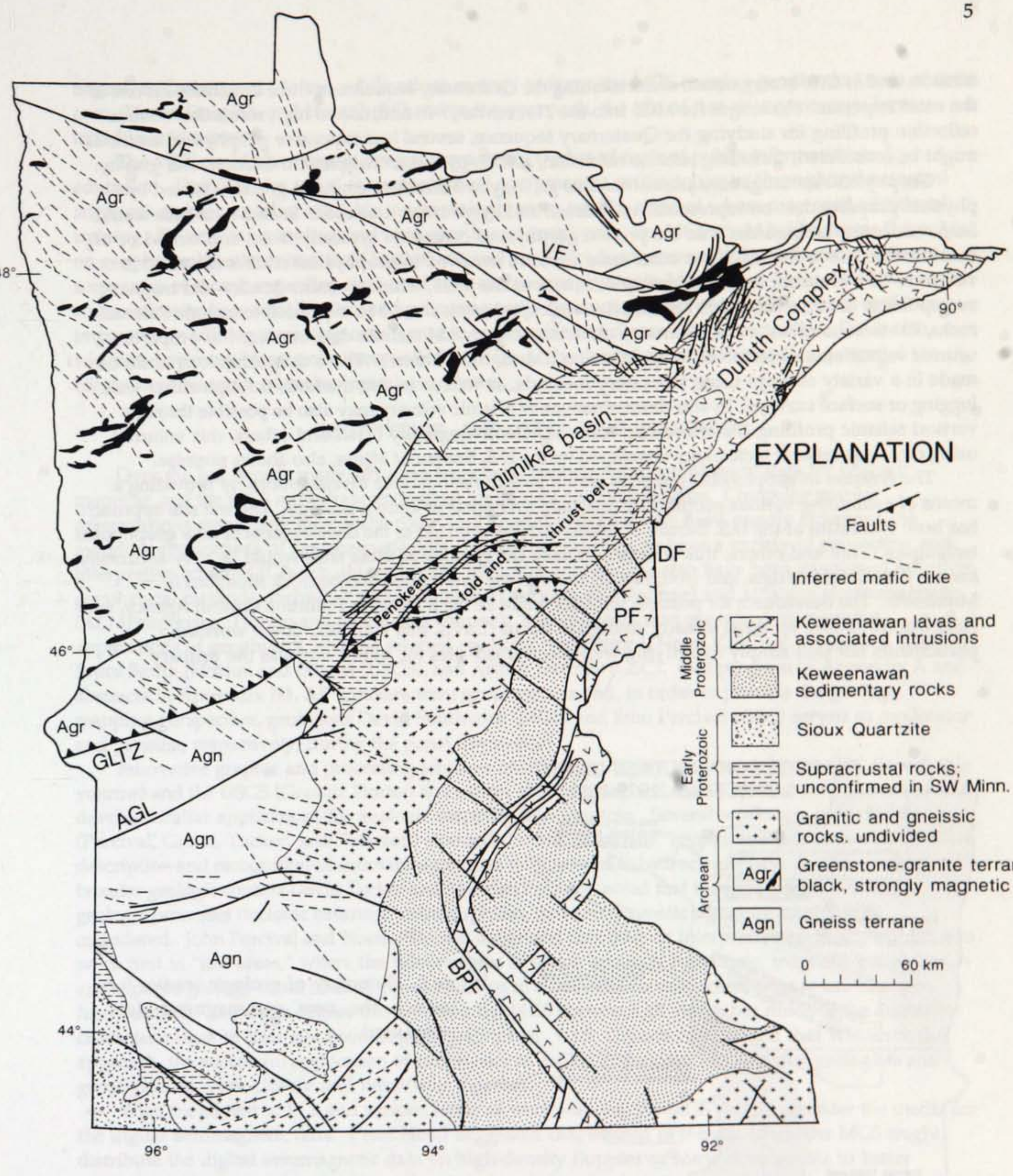

Figure 3. Generalized Precambrian geologic map of Minnesota. Compilation based on published and unpublished sources at the Minnesota Geological Survey, supplemented by interpretation of the LCMR gravity and aeromagnetic data. Strongly magnetic units within the greenstone-granite terrane shown in black. Mafic dikes largely inferred from the aeromagnetic data. AGL, Appleton geophysical lineament; BPF, Belle Plaine fault; DF, Douglas fault; GLTZ, Great Lakes tectonic zone; PF, Pine fault; and VF, Vermilion fault.

mission, and as G.B. Morey noted, understanding the Quaternary sequence in three dimensions is one of the most important challenges for MGS into the 21st century. In addition to high-resolution seismic reflection profiling for studying the Quaternary sequence, several less expensive geophysical methods might be considered, including seismic refraction, resistivity, electromagnetic induction, and gravity.

Geophysical investigations of near-surface geology in Minnesota could be greatly assisted by physical property data on representative bedrock and overburden materials. Such a data base would help reduce the ambiguities that the private geophysical contractor typically faces, and would be of considerable use to the MGS and other state agencies involved in geophysical studies (Davis, this volume). The present physical property data base at the MGS, which contains density and magnetic susceptibility data for about 700 Precambrian rock specimens, should be expanded to include Paleozoic rocks, Cretaceous rocks, and Quaternary materials, and should include data on electrical properties, seismic velocities, and remanent magnetization (Davis, this volume). These determinations could be made in a variety of ways using laboratory methods, as well as in-situ methods through either well logging or surface surveys. In-situ determinations of seismic velocity may also be possible through vertical seismic profiling (Petersen, this volume). Geotomography (Thill and others, this volume), using crosshole seismic technology developed by the U.S. Bureau of Mines, also shows promise.

The creation of geophysical test sites would benefit near-surface investigations by providing a means of evaluating various geophysical methods over areas of known geology. The test site approach has been successful at the U.S. Bureau of Mines and has even led to the development of new geophysical techniques (Thill and others, this volume). Ideally the geology of these sites would be very accurately known from borehole data, and would typify some of the overburden and bedrock situations in Minnesota. The best source for possible test sites might be the Minnesota Pollution Control Agency, who have extensive files on areas already studied in detail (Davis, this volume). Some workshop participants felt that simply identifying well-constrained sites for public use was the primary

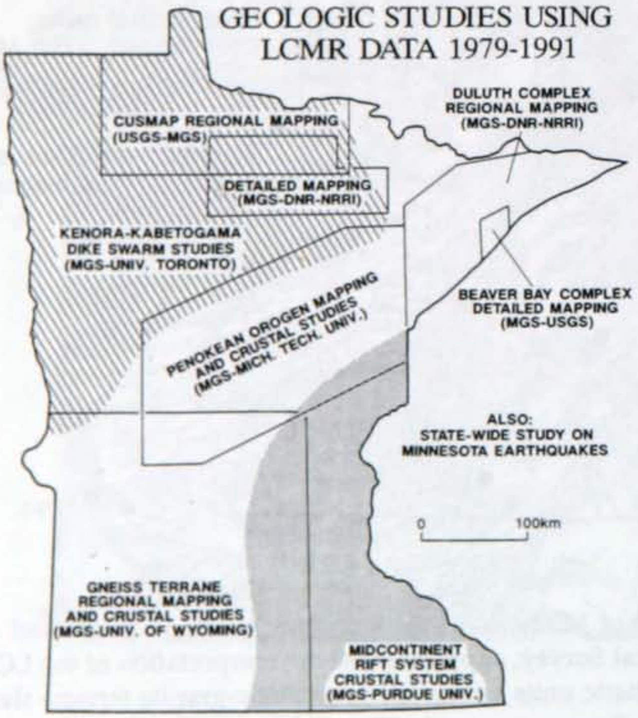

Figure 4. Summary of geologic studies for which the new aeromagnetic data were used.

objective (Corbett and Morey), while others seemed to favor the MGS running geophysical tests of their own (Davis, Steeples, and Hinze). Whatever the approach, the use of test sites appears to have a broad base of support.

The MGS could also serve in several ways under the broad topic of public information and education. Don Steeples noted that geophysical equipment is getting cheaper through technological advances and is becoming available to increasingly more people, some of whom may need additional training. To help safeguard against improper use of geophysics, the MGS could help educate the public on geophysical methods and their limitations, and could produce some sort of standards or, at least, some rules of thumb regarding the use of near-surface geophysics in Minnesota. Philip Davis noted that communication between all public and private agencies conducting geophysics in Minnesota could be improved by holding a meeting once a year to summarize and discuss current activities. Davis also suggested opening communications with the "State Archeologist" to see if there is any potential for cooperative research in archeological geophysics.

GEOPHYSICS AND GEOLOGIC MAPPING

Over the last decade many advances have been made in using geophysical data for geologic mapping, and the MGS must draw upon these for its own mapping mission. Computer graphic presentations employing gray-scale, color, and shaded-relief formats have greatly enhanced the mapping applications of aeromagnetic data (Hood, this volume), as have a variety of processing and interpretive schemes (Grauch, this volume). Mapping applications also have been developed for other geophysical methods, including aeroradiometric (Darnley, this volume) and airborne electromagnetic (AEM) surveying (Horton and others, this volume). A session was thus organized on mapping applications of geophysics, and the selected speakers were Peter J. Hood (GSC), V.J.S. Grauch (USGS), Bruce Smith [Horton and others] (USGS), and Arthur Darnley (GSC). (See program in Appendix A and abstracts in Appendix B.) All speakers were geophysicists and, in order to provide the geologic mapping perspective, geologists David Southwick (MGS) and John Percival (GSC) served as moderator and panelist, respectively, during the panel discussion.

Innovative graphic and processing schemes have proven highly successful for the GSC (Hood, this volume) and the USGS (Grauch; Horton and others, this volume), and the MGS must continue to use and develop similar applications for geologic mapping in Minnesota. Several workshop participants (Percival, Green, Tucker, and Paterson) stressed the importance of "texture analysis"—the quantitative description and recognition of anomaly signatures with respect to bedrock geology. In a somewhat broader geologic context David Tucker and Norman Paterson noted that the connections between geologic processes (tectonic suturing, metamorphism, etc.) and magnetic signature must also be considered. John Percival and Norm Paterson suggested that the best interpretive approach would be to work first in "test areas," where the relationships between anomaly signatures, magnetic properties, and exposed geology could be determined and then to move out into unexposed areas to use what you have learned. To a large degree this has been the MGS approach all along, but much of the anomaly characterization to date has been largely qualitative. V.J.S. Grauch commented that whatever the approach, the successful application of geophysics to geologic mapping requires that geologists and geophysicists work closely and iteratively together.

With the advent of PCs and various kinds of work stations, the MGS should consider the media for the digital aeromagnetic data. Peter Hood suggested that instead of 9-track tapes, the MGS might distribute the digital aeromagnetic data on high-density floppies or some other media to better accommodate PC-based users. Bruce Smith stressed that the digital aeromagnetic data, together with all other geophysical and geologic data used in mapping by the MGS, should ultimately be brought into a common Geographic Information System (GIS), as is being done at the USGS.

Scientific test drilling, which provides the only ground truth in bedrock mapping of till-covered areas, should be continued as an integral part of geophysical interpretation, and the MGS should make efforts to maximize the information from each drill hole. John Percival said that mapping the concealed basement of western Canada has been greatly facilitated by age dating and the full spectrum of geochemical analyses on drill hole samples. David Southwick responded that the MGS is keenly interested in such an approach, but to date no funds have been available.

Costs and limitations resulting from the overburden continue to discourage the large-scale acquisition of airborne radiometric and EM data for general mapping purposes, but the methods might be useful for carefully defined problems. Passive airborne EM methods, such as very low frequency (VLF) and 60 cycle, are relatively inexpensive and have shown sensitivity to till and bedrock features in the CUSMAP area of north-central Minnesota (Horton and others, this volume). Dramatic improvements have been made over the last decade in the geologic mapping applications of the aeroradiometric method in Canada (Darnley, this volume; Ford, poster presentation). In well-exposed areas many rock types can be directly identified from processed gamma-ray spectrometer data, and in areas of thin till cover, some glacial deposits can be traced to bedrock origins. Arthur Darnley noted that over the thick, multiple till sheets that cover much of Minnesota, no bedrock applications are likely, although some radiometric applications to glacial geology might be developed.

GEOPHYSICS AND MINERAL EXPLORATION

Mineral exploration was initially the primary justification of the aeromagnetic survey program, and it continues to be a major justification for much of the geoscientific research in the state. A workshop session was organized to assess the present geophysical needs of the mineral exploration community. The speakers were consultant John D. (Jack) Corbett, Norman Paterson of Paterson, Grant and Watson Ltd., Melvyn Best of the GSC, Juha Korhonen of the Geological Survey of Finland, and David Tucker of Preview Resources Ltd. (See program in Appendix A and abstracts in Appendix B.) In addition to the speakers, Allan Spector of Spector and Associates Ltd. and private consultant Rodney J. Ikola participated in the panel discussion.

The speakers agreed that the MGS could best help mineral exploration in Minnesota by interpreting its aeromagnetic data for geologic mapping. According to Rodney Ikola, this recommendation was given the highest priority by the Minnesota Exploration Association. Interpretation of the magnetic data should incorporate characterization of anomaly signatures or "texture analysis" (Paterson, this volume) perhaps somewhat along the lines of the so-called "geomag maps" that were recently produced in South Australia (Tucker, this volume). Quantitative characterization of anomalies for geologic mapping may be a promising direction of research; Juha Korhonen described one such mapping application being developed in Finland that employs an "unsupervised self-organizing" procedure through neural networking of computers. Allan Spector stressed that aeromagnetic interpretation should be done together with interpretation of other geophysical data, such as gravity and rock properties. Spector and Ikola stated that in addition to analysis of gridded data, interpretation should incorporate flight profile data, which commonly contain more information. Norman Paterson and Jack Corbett agreed that good geologic maps produced through synthesis of existing geophysical and geologic data would be one of the most significant enticements to bring explorationists into Minnesota.

The digital aeromagnetic data should be made available on high-density floppy disks or other media that are compatible with PC-based work stations. According to Rodney Ikola, this task is another high-priority item with the Minnesota Exploration Association. Jack Corbett stated that the present medium of coded 9-track tapes can be easily handled by facilities at larger companies, but cannot be handled by smaller operators who usually have only a PC at their disposal. Most of the panelists believed that both the gridded data and the flight profile data should be available on high-density floppy disks and that area-specific orders should be possible. Corbett and some other participants did not favor high-capacity media such as CD-ROMs, because many smaller operators cannot handle them. On the other hand, high-capacity media appear to be the tools of the future

(Tucker) and it still might be prudent for the MGS to transfer all aeromagnetic data to a compact medium such as CD-ROM for archiving and in-house use.

Improving the rock properties data base in Minnesota would greatly benefit explorationists working in Minnesota, and would certainly assist the MGS in its interpretive mapping. Essentially all speakers and panelists in this session seemed to favor such an effort. As noted above in the section on near-surface geophysics, the present rock properties file includes density and magnetic susceptibility data for only about 700 Precambrian rock samples. In contrast, the rock properties file compiled by the Geological Survey of Finland contains over 40,000 entries (Korhonen, this volume). In addition to increasing the number of determinations and rock units, the MGS file should be expanded to include data on NRM, seismic velocities, and electrical properties. Rodney Ikola noted that the dynamic range in electrical resistivities of earth materials in Minnesota is astonishingly wide; he has observed resistivities as low as 10 ohm-m for some clays and as high as 100,000 ohm-m for some bedrock. Given this situation, having the means to estimate electrical properties for a given geologic unit would clearly help explorationists in both field design and interpretation of their electrical and electromagnetic surveys.

As noted above in the section on near-surface studies, the thickness of the glacial overburden is of considerable interest to mineral explorationists. Seismic methods may be the most effective for this type of study, but they are expensive and the areas needing better control are quite large. During this session some participants discussed how less expensive geophysical methods might be used to supplement the seismic studies. Norman Paterson and Allan Spector suggested using magnetic anomaly depth estimates for at least a starting point in areas of Precambrian bedrock. Gravity studies using the existing data base and selected profiles might be useful (Tucker), although uncertainties about density could lead to considerable ambiguity in depth interpretation in some areas (Corbett). Melvyn Best and Charles Young proposed that sounding using ground-based EM methods might be effective, provided electrical property data from resistivity logs or other sources were available.

Some support was expressed for establishing mineral exploration test sites. As noted by Peter Hood, mineral test sites in Canada have been very well received by the Canadian exploration industry. Although no commercial deposits have been identified in Minnesota apart from iron ore, the DNR maintains a file of geophysical case histories over anomalous areas that were subeconomic mineral deposits or barren, and it is possible that several candidate sites could be selected representing a variety of overburden conditions.

Airborne EM remains too expensive and too vulnerable to conductive overburden to be applied as a general mapping tool in Minnesota, but it might be useful for carefully defined problems. Using examples from the clay belt region near Timmins, Ontario, Best (this volume) demonstrated that the modern AEM methods are capable of detecting some bedrock conductors even where there is a considerable sequence of conductive overburden. Moreover both AEM and ground-based EM methods are being used more and more to investigate the overburden itself; Best also demonstrated that AEM could be useful for mapping overburden thickness, provided that the overburden resistivities could be constrained by drill hole logs or other data. T.J. McConnell of Questor Surveys Ltd. noted that digital analysis and other technological advances were rapidly changing AEM methods from target finding to true mapping, and that generation of conductivity/thickness sections along lines and 3-D conductivity interpretations of grids will probably become standard procedure within the next few years.

GEOLOGY IN THREE DIMENSIONS: THE USE OF GEOPHYSICS IN CRUSTAL STUDIES

The Precambrian terranes of Minnesota provide a window on crustal evolution and structure for central North America. Since the start of the MGS aeromagnetic program, several important crustal studies have been made in the region; among these are seismic reflection investigations of the Great Lakes tectonic zone and gneiss terrane of southwestern Minnesota by COCORP (Consortium on

Continental Reflection Profiling) and more recently by the University of Wyoming (Boyd, this volume); seismic reflection studies in the Lake Superior region by GLIMPCE (Great Lakes International Program on Crustal Evolution) and related projects (Hinze, this volume); and magnetotelluric studies of the Penokean orogen and Midcontinent rift system by Michigan Technological University (Young, this volume). A workshop session was organized to consider future options for crustal studies in Minnesota and to determine what roles MGS might assume in these studies. Speakers for this session were R.H. Sutcliffe (University of Western Ontario), N. Boyd (University of Wyoming), C.T. Young (Michigan Technological University), J.A. Percival (GSC), E.A. Atekwana (Western Michigan University), H.C. Halls (University of Toronto), A.G. Green (GSC), and W.J. Hinze (Purdue University). (See program in Appendix A and abstracts in Appendix B.) In addition, Professor Subir K. Banerjee of the Dept. of Geology and Geophysics at the University of Minnesota gave a brief presentation on the new paleomagnetic research center being established at the University of Minnesota.

Seismic investigations associated with COCORP, GLIMPCE, and the Canadian LITHOPROBE Project have demonstrated that many Precambrian structures produce prominent reflection signatures that are not unlike those associated with their probable counterparts in Phanerozoic terranes (Green, this volume). LITHOPROBE seismic reflection data from the Abitibi greenstone belt reveal listric thrust faults cutting the sequence, and have helped lead to a model of arc accretion for the southern Superior Province (Sutcliffe, this volume). Seismic reflection data from the Kapuskasing structure have shown it to be a deep crustal uplift along a major shear, and the highly reflective and thickened crust interpreted beneath the structure has provided the basis for a new tectonic model for the structure (Percival, this volume). Seismic reflection studies in Lake Superior and on surrounding regions by GLIMPCE and related projects have revealed that crustal structure beneath the Midcontinent rift system includes volcanic basins several tens of kilometers thick, deep-seated growth faults that were later reversed into thrusts, and significantly thickened crust (Hinze, this volume).

As promising as deep seismic reflection methods are for crustal studies in Minnesota, the potential of less expensive geophysical methods should not be overlooked. Gravity model studies, together with magnetic anomaly and rock property data, can be an extremely effective supplement to seismic interpretations of the crust (Atekwana, this volume). William J. Hinze noted that with the satellite-based Global Positioning System, gravity surveying will become much cheaper in remote parts of Minnesota. In addition, magnetotelluric methods have proven to be a very effective, low-cost means of studying crustal structure in Minnesota (Young, this volume). Finally, the structure in the uppermost crust is generally lost on most deep seismic reflection data, and high-resolution seismic reflection data for near-surface investigation could help in relating structures indicated on deep seismic sections to geology mapped at the surface.

The MGS is favorably situated to promote and organize crustal studies in cooperation with other institutions. Through its broad mission of mapping and framework studies, the MGS can recognize significant crustal problems and can help focus crustal studies on specific problems. A critical mass of institutions already exists for crustal studies in the region. The University of Wyoming (Boyd, this volume) and Michigan Technological University (Young, this volume) are actively contributing to crustal studies in the state, and other organizations might be attracted to well-defined and solvable problems. Richard Sutcliffe and others at the workshop suggested a mini-consortium of U.S. and Canadian institutions working southward from about Red Lakes, Ontario, either to the Archean gneiss terrane in Minnesota or to Lake Superior. Such a study would yield major insights into the crustal structure along the southern margin of the Superior Province, and the international aspect might help attract federal funding on both sides of the border.

On a somewhat different tack, the MGS should encourage paleomagnetic studies aimed at crustal-scale problems. Paleomagnetic studies of diabase dikes near Lake Superior and across the Kapuskasing structure have been useful in determining such subtle parameters as uplift and degree of regional tilting, and similar procedures could be applied in the Archean and Proterozoic terranes of Minnesota (Halls, this volume). Paleomagnetic studies combined with high-resolution radiometric dating could provide some badly needed anchor points on the apparent polar wander (APW) path for Early Proterozoic North America (Halls, this volume). The Paleomagnetic Research Center being established by Professor Banerjee and co-workers at the University of Minnesota, will be particularly well suited for unraveling the complex, multi-stage magnetizations that typify many Precambrian rocks.

SUMMARY AND RECOMMENDATIONS

Many excellent recommendations were produced from this workshop, but in sobering truth, it would take an organization many times the size of the MGS several decades to implement them all! The MGS will need to concentrate on the highest priority recommendations developed by the workshop. These are summarized below, and they comprise the strategy for the MGS geophysics activity into the future.

Recommendation 1. (top priority).

By far the strongest recommendation from the workshop is that the MGS should continue to use its aeromagnetic and gravity data for geologic mapping. This recommendation was repeated throughout the workshop and, in light of the MGS geologic mapping mission and its excellent aeromagnetic and gravity data bases, it is indeed a very logical one. Most bedrock mapping done to date in Minnesota (Figs. 3 and 4) has been at a regional scale (1:250,000 or smaller) and more detail should now be possible in many areas. Moreover the regional mapping itself can be significantly improved. Near the close of the workshop, Norman Paterson stated that systematic regional mapping is probably the single most valuable contribution that the MGS can make to private companies, who usually have neither time nor money to do it themselves. David Southwick concurred, adding that if the geologic mapping is done properly, it can serve as a solid foundation for a variety of public uses.

In using geophysics for geologic mapping, the MGS must upgrade its own processing and interpretation software, along the lines of some of the innovative techniques discussed at the meeting. Particularly promising approaches are those that analyze the texture of anomalies or correlate several geophysical data sets, ultimately relating patterns in the processed data to geology. Research on how broad geologic processes affect magnetic minerals and, consequently, anomaly signatures should also be pursued. Test drilling should be continued as an integral part of interpretation and the MGS should endeavor to maximize the information from each drill hole through petrology, geochemistry and, if possible, high-precision age dating. Combining geophysical interpretation with test drilling and field mapping to produce geologic maps has already proven successful in Minnesota and accelerated work along these lines is certain to satisfy a broad range of needs well into the future.

Recommendation 2.

The MGS should expand its work on physical properties (magnetic, electrical, and seismic) of earth materials. This recommendation was made repeatedly during the workshop sessions by a diversity of interests. In addition, the representative of the Geological Survey of Finland (Korhonen) expressed interest in bilateral work with MGS on this topic of mutual interest to both surveys. In both ground-water investigation and mineral exploration, physical property data on bedrock and overburden materials can be crucial in the selection of geophysical methods and survey design, and can play a major role in the interpretation of the subsequent data. Physical property data are also important to the geologic mapping mission of the MGS in that they assist considerably in connecting a given geophysical signature to a rock type. The rock properties file at the MGS consists of about 700 density and magnetic susceptibility measurements derived from a somewhat limited suite of Precambrian rocks. This data base must be enlarged and include properties such as remanent magnetization, seismic velocities, and electrical characteristics. The data base should also include Paleozoic, Cretaceous, and Quaternary materials. Much of the work could be achieved through laboratory measurements, although in-situ determinations through well logging and field studies should also be included.

Recommendation 3.

Increased use of geophysical methods to study Minnesota's Quaternary materials, whose thickness and stratigraphy is very poorly known in many parts of the state, will aid in investigations ranging from ground water to minerals and accord well with the geologic mapping mission of the MGS. To some degree the MGS is already pursuing geophysical studies of Quaternary materials through the county atlas program, where seismic data acquired through cooperation with the Waters Division of the DNR are being used chiefly to determine depth to bedrock. However, the atlas projects to date have been for counties in southeastern Minnesota, and data for other parts of the state are needed. In order to study the Quaternary sequence effectively, the MGS should become more involved with seismic methods, in particular seismic reflection. Methods that are cheaper than seismic reflection should also be considered, including gravity, electrical, and electromagnetic methods. The best approach may be first to conduct studies in test areas using a variety of geophysical methods under a variety of overburden and bedrock conditions. The results of this preliminary study could then be used to form cost-effective strategies for geophysical studies of the Quaternary sequence elsewhere in the state. As to what new geophysical capabilities the MGS might need, and as to how the MGS might dovetail with DNR Division of Waters will have to be established as related projects develop.

Recommendation 4.

The MGS should make the digital aeromagnetic data available in media that are more compatible with PC-based technology than 9-track tapes. The need for new media, which was expressed most strongly during the workshop sessions on geologic mapping and mineral exploration, includes both the gridded and the recovered flight path data. Some workshop participants preferred that the data be available on standard floppy discs on an area-specific basis, whereas others simply wanted all of the data available en masse on CD-ROM or similar high-density media. The MGS should consider both approaches, and begin evaluating the technologies and organizations that might best provide these services. The National Geophysical Data Center, which is the principal distributor of the MGS aeromagnetic flight path data, has gained considerable expertise in the distribution and management of digital data, and should be consulted. Transferring the digital aeromagnetic data to new media is going to take some careful planning, but by tackling this problem the MGS can tremendously expand the utility of the digital data to more users.

Recommendation 5.

The creation of geophysical test sites was endorsed during the sessions on near-surface geophysics, mineral exploration, and geologic mapping. Ideally these test sites should encompass a range of bedrock and overburden conditions that exist in Minnesota, and the studies should employ the full gamut of geophysical methods. For shallow geophysical sites the MGS could consult with the PCA, who have extensive files on areas that are well constrained by drill hole data. The case history files available at the DNR could serve as a starting point for selecting mineral exploration test sites: numerous prospects have already had many geophysical methods applied to them. To a large degree we have already been using a test-site approach with regard to geologic mapping. In the Cook area, for example, exposures were used to establish the characteristic relationships between geophysical signatures and geology, and these were extrapolated to covered areas. Acceleration of geologic mapping would naturally require, as well as produce, added insight into correlation of geophysical results and ground truth.

Recommendation 6.

The MGS should encourage fundamental research into broad scientific problems regarding regional tectonics and crustal structure. The Precambrian bedrock of Minnesota records several major events that formed the North American craton, and our knowledge of these events and their relationship to present-day crustal structure remains sketchy. The MGS could encourage research by identifying key tectonic features and problems through its mapping programs, and then help organize mini-consortia with nearby institutions who may have the resources to investigate these features.

Work in Progress

Some of the workshop recommendations were for techniques that the MGS was already using. In the Cook and Isabella areas, for example, MGS had accelerated the processing and interpretation of the aeromagnetic and gravity data and expanded the rock property data as part of a geophysical test-site approach to geologic mapping that included test drilling. Other recommendations are being implemented. For example, the MGS is looking into the transfer of the digital aeromagnetic data to PC-friendly media. In consultation with the National Geophysical Data Center, plans are being made for duplicating all MGS flight profile data to CD-ROM. In the course of ongoing use of geophysical methods, the MGS will continue to find new applications, such as those reported on posters by McSwiggen, Runkel, and Setterholm (this volume). These initial steps are very encouraging, but much geophysical work clearly remains to be done. If heeded, the strategy formulated at this workshop should bring Minnesota geophysics successfully into the 21st century.

ACKNOWLEDGMENTS

As indicated in the preface and the introduction, the Minnesota Geological Survey gratefully acknowledges the support provided to the aeromagnetic survey and to the workshop by the Legislative Commission on Minnesota Resources. We also wish to thank the U.S. Geological Survey and the Geological Survey of Canada for allowing staff members to attend, and for covering some of their expenses. Lori Day of the MGS provided invaluable assistance with correspondence and day-to-day organizational tasks. We wish to thank several others of the MGS staff who assisted at the Workshop, including Jay Vu, Jacqueline Duley, Sanghamitra Sahu, and Mike Olson, who helped with the audio-visual equipment, and Angela Gowan, Peter McSwiggen, Terry Boerboom, and Mark Jirsa who served as note takers. The workshop was organized with the very capable help of the Professional Development and Conference Services at the University of Minnesota.

APPENDIX A

PROGRAM

GEOPHYSICAL SOLUTIONS TO GEOLOGIC PROBLEMS OF CONTINENTAL INTERIORS: A MINNESOTA WORKSHOP

held March 3-6, 1991 at the
Radisson Hotel Metrodome, Minneapolis, Minnesota

Sunday, March 3, 1991

5:00 - 7:00 p.m.
Welcoming icebreaker and registration (cash bar)

Monday, March 4, 1991

SESSION 1. MINNESOTA GEOPHYSICS AT THE CROSSROADS
Chair: Priscilla C. Grew (director, Minnesota Geological Survey)

7:45 a.m.
Registration and coffee

8:20 a.m.
Welcome and announcements
Val W. Chandler (geophysicist, Minnesota Geological Survey)

8:30 a.m.
Geophysics and the geologic mapping mission of the Minnesota Geological Survey
Priscilla C. Grew (director, Minnesota Geological Survey)

8:50 a.m.
The LCMR-MGS aeromagnetic survey program: an innovative approach to natural resource funding. Matt Walton (director emeritus, Minnesota Geological Survey) and Robert E. Hansen (director emeritus , Legislative Commission on Minnesota Resources)

9:00 a.m.
Minnesota's geological framework and pertinent geophysical problems
G.B. Morey (associate director, Minnesota Geological Survey)

SESSION 2. STARTING AT THE TOP: GEOPHYSICS IN THE INVESTIGATION OF NEAR-SURFACE GEOLOGY
Co-chairs: Kenneth L. Harris and Dale R. Setterholm (Minnesota Geological Survey)

9:30 a.m.
Uses of shallow seismic methods in solving geologic problems: a state agency perspective
Don W. Steeples (Kansas Geological Survey)

10:00 a.m.
Geophysical mapping of regional geology and water resources
Todd A. Petersen (Minnesota Department of Natural Resources, Division of Waters)

10:30 a.m.
Coffee break

11:00 a.m.
Geosolutions to mining problems: Bureau of Mines Research
Richard E. Thill (U. S. Bureau of Mines)

11:20 a.m.
Applications of near-surface geophysical investigations in Minnesota
Philip A. Davis (Private Consultant - Geosphere Midwest Inc.)

11:50 a.m.
Panel Discussion. Don W. Steeples (Kansas Geological Survey) presiding.
Panelists: Davis, Morey, Petersen, Setterholm, Thill

12:30 p.m.
Lunch on your own

SESSION 3. GEOPHYSICS AND GEOLOGIC MAPPING

Co-chairs: Mark A. Jirsa (Minnesota Geological Survey) and Bruce D. Smith (U. S. Geological Survey)

2:00 p.m.
Aeromagnetic surveying: present and future perspectives
Peter J. Hood (Geological Survey of Canada)

2:30 p.m.
Innovations in the interpretation of regional gravity, magnetic, and airborne EM data sets
V. J. S. Grauch (U. S. Geological Survey)

3:00 p.m.
Interpretation of new airborne geophysical data-Effie-Coon Lake area, Minnesota
Bruce D. Smith [see Horton and others, this volume] (U. S. Geological Survey)

3:30 p.m.
Coffee break

3:50 p.m.
Geologic applications of airborne radiometric data
Arthur G. Darnley (Geological Survey of Canada)

4:20 p.m.
Panel Discussion. David L. Southwick (Minnesota Geological Survey), presiding.
Panelists: Darnley, Grauch, Hood, Percival, and Smith

5:00 p.m.
Dinner on your own

7:00 p.m.
Poster Session (informal conversation, beer keg on tap)

9:00 p.m.
Adjourn

Tuesday, March 5, 1991

SESSION 4. GEOPHYSICS AND MINERAL EXPLORATION

Co-chairs: Rodney J. Ikola and John D. Corbett (independent consultants)

8:30 a.m.
Trends in geophysical practice for base and precious metal exploration
John D. Corbett (independent consultant)

9:00 a.m.
Progress in the geologic interpretation of aeromagnetic surveys
Norman R. Paterson (Paterson, Grant & Watson Ltd.)

9:30 a.m.
Electromagnetic prospecting in overburdened areas: examples from Canada
Melvyn E. Best (Geological Survey of Canada)

10:00 a.m.
Coffee break

10:20 a.m.
Contribution of aerogeophysical survey programs to mineral resource assessment, prospecting, bedrock mapping and crustal studies in Finland
Juha V. Korhonen (Geological Survey of Finland)

10:50 a.m.
Integrated uses of airborne geophysical data for geologic mapping and mineral exploration in Australia
David H. Tucker (Preview Resources, Inc.)

11:20 a.m.
Panel Discussion. Norman R. Paterson (Paterson, Grant & Watson Ltd.), presiding.
Panelists: Best, Corbett, Ikola, Korhonen, Spector, and Tucker

12:30 p.m.
Lunch on your own

SESSION 5. GEOLOGY IN THREE DIMENSIONS: THE USE OF GEOPHYSICS IN CRUSTAL STUDIES

Co-chairs: Val W. Chandler (Minnesota Geological Survey) and Alan G. Green (Geological Survey of Canada)

2:00 p.m.
Crustal structure of the Abitibi greenstone belt: new models from geological and geophysical data. Richard H. Sutcliffe, S. L. Jackson, and V. K. Gupta (University of Western Ontario and Ontario Geological Survey)

2.30 p.m.
Seismic reflection studies of the Archean: the gneiss terrane of southern Minnesota
Nick Boyd (University of Wyoming)

3:00 p.m.
Deep electromagnetic studies of Precambrian terranes in the Lake Superior region
Charles T. Young (Michigan Technological University)

3:30 p.m.
Coffee break

4:00 p.m.
Geological and geophysical insights on the structure and evolution of the Superior Province
John A. Percival (Geological Survey of Canada)

4:20 p.m.
Crustal structure of the Kapuskasing structural zone: constraints from gravity modeling
Estella A. Atekwana (Western Michigan University)

4:50 p.m.
Minnesota Research Center on Paleomagnetic Research: future research directions
Subir K. Banerjee (University of Minnesota)

5:00 p.m.
Dinner on your own

7:00 p.m.
Poster Session (informal conversation, beer keg on tap)

9:00 p.m.
Adjourn

Wednesday, March 6, 1991

SESSION 5. CONTINUED
Co-chairs: Val W. Chandler (Minnesota Geological Survey) and Richard H. Sutcliffe (Ontario Geological Survey)

8:30 a.m.
The use of paleomagnetism in Precambrian terranes
Henry C. Halls (University of Toronto)

9:00 a.m.
Diverse seismic reflection images from the Canadian Shield
Alan G. Green, B. Milkereit, and D. Forsyth (Geological Survey of Canada)

9:30 a.m.
The role of regional geophysical studies in the Midcontinent: new views on an ancient rift
William J. Hinze (Purdue University)

10:00 a.m.
Panel Discussion. William J. Hinze (Purdue University), presiding.
Panelists: Atekwana, Boyd, Green, Halls, Percival, Sutcliffe, and Young

10:30 a.m.
Coffee break

SESSION 6. SUMMING UP

Chair: Priscilla C. Grew (Minnesota Geological Survey)

10:45 a.m.
Directions for the future: development of workshop recommendations
Panel discussion with audience participation: Chandler, Green, Hinze, Ikola, Percival, Smith, Southwick

11:10 a.m.
Adjourn

POSTER SESSIONS

All posters are to be on display from 6:30 p.m. March 4 to 10:00 a.m. March 6.

Melvyn E. Best (Geological Survey of Canada). Electromagnetic prospecting in overburdened areas: examples from Canada.

Nick Boyd (University of Wyoming). Seismic reflection studies of the Archean: the gneiss terrane of southern Minnesota.

Val W. Chandler (Minnesota Geological Survey). Minnesota aeromagnetic surveying program.

Val W. Chandler, Terrence J. Boerboom, Mark A. Jirsa (Minnesota Geological Survey). Geophysical interpretation, test drilling, and geologic mapping in the Cook Area, Minnesota.

Val W. Chandler, Steve Hauck, Mark Severson, John Heine, Jane Reichoff (Natural Resources Research Institute). Investigation of kaolin in eastern Redwood County, Minnesota, using gravity, magnetic, and electrical methods.

Val W. Chandler, James D. Miller, Jr. (Minnesota Geological Survey). Geophysical interpretation, test drilling, and geologic mapping in the Isabella area, Minnesota.

Arthur G. Darnley (Geological Survey of Canada). International geochemical mapping.

Philip A. Davis (Geosphere Midwest, Inc.). Applications of near-surface geophysical investigations in Minnesota.

Michael J. Friedel, James J. Jessop, Richard E. Thill (U. S. Bureau of Mines). Common offset radar profiling for detection of fractures in igneous rock.

Ken L. Ford (Geological Survey of Canada). Mapping and exploration applications of airborne gamma ray spectrometry: some examples.

Alan G. Green, B. Milkereit, D. Forsyth (Geological Survey of Canada). Diverse seismic reflection images from the Canadian Shield.

V. J. S. Grauch (U. S. Geological Survey). Innovations in the interpretation of regional gravity, magnetic, and airborne EM data sets.

Jay C. Hanson, Michael J. Friedel, Daryl R. Tweeton (U. S. Bureau of Mines). Fluid detection using electromagnetic geophysics.

Robert J. Horton, Bruce D. Smith, Victor L. Labson, Robert J. Bisdorf (U. S. Geological Survey). Interpretation of new airborne geophysical data: Effie-Coon Lake area, Minnesota.

Juha V. Korhonen (Geological Survey of Finland). Contribution of aerogeophysical survey programs to mineral resource assessment, prospecting, bedrock mapping and crustal studies in Finland.

John Mariano and William J. Hinze (Purdue University). Investigations of the Midcontinent Rift using variable magnetization forward modeling and inversion.

Peter L. McSwiggen (Minnesota Geological Survey). A new device for logging the resistivity of drill core and its use in research on carbonaceous metasedimentary rocks.

John A. Percival (Geological Survey of Canada). Geological and geophysical insights on the structure and evolution of the Superior Province.

Todd A. Petersen (Minnesota Department of Natural Resources). Geophysical mapping of regional geology and water resources.

Anthony C. Runkel (Minnesota Geological Survey). The use of downhole geophysical logs in a hydrologic survey.

Dale R. Setterholm (Minnesota Geological Survey). Downhole geophysical logging program.

Allan Spector, Robert Ferderer, Tom Lawler, and Edward Venzke (Minnesota Department of Natural Resources, sponsor). Pseudogeologic maps: preparation and use.

David H. Tucker (Preview Resources, Ltd.). Integrated uses of airborne geophysical data for geologic mapping and mineral exploration in Australia.

Charles T. Young (Michigan Technological University). Deep electromagnetic studies of Precambrian terranes in the Lake Superior region.

APPENDIX B

ABSTRACTS

CRUSTAL STRUCTURE OF THE KAPUSKASING STRUCTURAL ZONE: CONSTRAINTS FROM GRAVITY MODELING.

Estella A. Atekwana
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Kalamazoo, Michigan

The Kapuskasing Structural Zone (KSZ) in northwestern Ontario is a northeast-trending belt of high-grade metamorphic rocks. Based on its characteristic gravity and magnetic signatures, the KSZ has been subdivided into four tectonic blocks—the Chapleau Block (CB), the Groundhog River Block (GRB), the Val Rita block (VRB) and the Fraserdale-Moosonee Block (FMB). Using 1400 new gravity stations, a detailed gravity study constrained by magnetic and seismic data was used to determine the crustal structure beneath the VRB, GRB, and CB.

Gravity and magnetic models across the VRB suggest that dense granulites initially at depths of 10-25 km have been uplifted to shallow crustal depths (1-4 km). These granulites are generally not exposed but are buried underneath a thin veneer of amphibolite-facies tonalitic gneiss. Furthermore, the models suggest that the crust is 48-50 km thick beneath the VRB and its associated gravity high, compared to 40-43 km beneath adjacent areas. Results also suggest that the granulites associated with the GRB are thin (1-4 km) and have been uplifted from depths comparable to those of the VRB. Model results from the CB are consistent with previous results and indicate that the dense granulites of this block have been uplifted from depths of 15-30 km to the surface. A thick crust of 53 km underlies the CB and is coincident with the high gravity anomaly.

The geometry of the VRB suggested by the potential field models is compatible with an antiformal structure at depth. Such a structure could have developed over a low-angle thrust plane, and was probably coeval with thrusting within the other blocks of the KSZ. A thin flat thrust sheet best describes the geometry of the GRB, while the CB is a west-dipping thrust slab. The interpreted geometries of the structures within the VRB, GRB, and CB are analogous to structures within the Phanerozoic fold and thrust belts, such as the Rockies, and may have important implications on the temperature of the granulites at the time of their uplift and hence, the age of the uplift.

ELECTROMAGNETIC PROSPECTING IN OVERBURDENED AREAS: EXAMPLES FROM CANADA

Melvyn E. Best
Pacific Geoscience Centre, Geological Survey of Canada
Sidney, British Columbia

A significant portion of the world's base metals are derived from massive sulphide deposits, many of which occur within the greenstone belts of volcanics and metasediments of the Canadian Shield. In particular the belts within the Precambrian Superior Province of Canada contain a significant number of economic sulphide deposits. The formations continue into the northern United States but Quaternary sediments cover most of the region. Massive sulphide exploration beneath conductive overburden has been ongoing in Canada for over 20 years. The experience in Canada can benefit future exploration activity in comparable regions of the northern United States.

Massive sulphide deposits are generally strong conductors with conductivities between 0.1 and 10 Siemans (S). The resistive volcanic and metasedimentary host rocks have conductivities between 0.1 and 10 milliSiemans (sM). Good conductors like massive sulphides are natural targets for electromagnetic (EM) prospecting systems. Indeed electromagnetic prospecting has been the preferred exploration method in Canada.

As already mentioned, parts of the Precambrian basement in Canada and the northern United States are covered with Quaternary sediments, which consist of clay, sand and gravel of variable lateral and depth extent. Each sediment type has a distinct conductivity range. The overall conductivity of these sediments ranges from 1 to 200 (or more) mS. The electromagnetic response of massive sulphide conductors under glacial sediments is more complex than the corresponding response without overburden. The EM response of conductive overburden interferes with the bedrock response and in some cases masks the bedrock response completely. A judicious combination of geophysical methods, for example gravity, EM, and refraction seismic, is commonly employed to separate bedrock conductors from spurious overburden EM responses.

The paper concentrates on electromagnetic methods because they are most often used for massive sulphide exploration. The first part illustrates the general type of EM response that occurs in areas covered by Quaternary sediments. The clay belt region near Timmins, Ontario, has conductive glacial sediments covering the Precambrian greenstone belts. A number of test surveys have been carried out using data from resistivity soundings, airborne and ground EM, and drilling. In the Timmins area up to several hundred meters of interbedded clay and gravel overburden covers the basement rocks. The basement (bedrock) conductors are graphitic schists with pyrite and minor pyrrhotite and massive sulphide deposits such as the Kidd Creek mine. They are usually narrow, almost vertically dipping bodies with strike lengths up to several thousand meters. The examples illustrate the large variation in the depth and lithology of the Quaternary sediments. Several examples exhibit the electromagnetic response of bedrock conductors covered with conductive sediments.

The second part is devoted to the interpretation of electromagnetic data from overburden-covered areas, and in particular to the separation of bedrock and overburden conductors. A scheme is presented for interpreting EM data based on non-linear inversion methods. It utilizes a one-layer overburden forward model coupled to an inversion program. When the inversion fits the data (the standard error is small), the one-layer model yields estimates of the conductivity and thickness of the overburden and the bedrock conductivity. The standard error computed during the inversion can be flagged if it is larger than a preset value. Often it is large because the choice of forward model for the data at hand, in this case the one-layer overburden model, is incorrect. When this happens the flagged data can be examined using other interpretation methods such as two and three dimensional modelling. A synthetic example has been developed to demonstrate these concepts.

In conclusion electromagnetic methods can be used effectively for massive sulphide exploration beneath Quaternary sediments if appropriate systems are used (broadband and deeply penetrating) and proper interpretation of the data is carried out.

SEISMIC REFLECTION STUDIES OF THE ARCHEAN: THE GNEISS TERRANE OF SOUTHERN MINNESOTA

N. Boyd, K. Gohl, W. Clement, and S.B. Smithson
Program for Crustal Studies, Department of Geology and Geophysics
University of Wyoming, Laramie

Many authors have suggested that the Archean crust differs in character from that of younger Phanerozoic crust. In addition, the mechanisms of crustal formation and the tectonic regimes present in the Archean are not well understood. In 1988 and 1990, the University of Wyoming seismograph crew collected a total of 58 km of vertical incidence CMP data along the exposures of the oldest rocks in the USA: the gneiss terrane of the Minnesota River Valley. The profile consists of 48-fold data acquired using the UW Vibroseis source and 192-channel recording system. The 9.6-km spread length gives good velocity control into the middle crust. In order to constrain the deeper velocity structure, a coincident wide-angle survey was undertaken in both years based on Vibroseis and quarry shots. The results of the CMP profile show that the upper crust is dominated by a major southeast-dipping event that extends laterally for 40 km and from 4 to 7 seconds vertically. In addition, there are other events, shallower and sub-parallel to the major reflector in the upper crust. The upper crustal sequence is interpreted to be a recumbent fold or thrust sheet dipping at 17 degrees to the southeast. Alternatively, the major reflection may be an upper crustal shear zone, while the other reflections may be related to folding and faulting in the crust. Unfortunately the lack of surface exposure makes near-surface interpretation difficult; however, either interpretation is consistent with the observed surface folding. The middle crust is marked by significant reflectivity but a lack of coherent, laterally extensive reflections. Preliminary modeling shows that these short reflections seen in the middle to lower crust are consistent with elongate intrusive bodies. For example, they could be representative of a metagabbro or metabasalt body in a more felsic medium. The lower crust shows a major coherent, multi-cyclic, sub-horizontal reflection sequence at 14 seconds, extending laterally for about 10 km. Tau - P transformation of the wide-angle data and subsequent external inversion shows that this event is consistent with a reflection from Moho depth. This Moho event is locally reminiscent of Phanerozoic Moho events and therefore presents the problem of why the Moho is imaged here, when it is not found at vertical incidence either in other similar terranes or even extensively here. The Minnesota River Valley Moho event presents new and contradictory information on the Archean Moho.

TRENDS IN GEOPHYSICAL PRACTICE FOR BASE- AND PRECIOUS-METAL EXPLORATION

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The decline of base-metal exploration and rise of interest in precious metals changed the mix and range of geophysical methods applied to exploration. In precious-metal epithermal environments in the Great Basin, most geophysical methods have some application; however, primary emphasis is on electrical methods, particularly several of the more recent EM developments. Exploration for porphyry systems and polymetallic massive sulfide targets follows a more traditional geophysical approach, but with increasingly more sensitive electronics and more sophisticated processing software. In today's market here is increased emphasis on base metals, particularly skarn mineralization, Cu-Au porphyry systems, and polymetallics where gold is a significant part of the mineralization.

Regional and detail-scale magnetics remain a basic tool particularly with tight line spacing and low flight-level surveys. Color maps, shaded relief, and several of the computed filters are important products used both by geological explorationists and experienced geophysical interpreters. Forward and inverse modeling with PC-based software is commonly available. Use of electronic navigation systems has significantly increased the quality of magnetic surveys.

Gravity methods have more use in relatively flat Archean terrains, than in the strong topographic relief of the Basin-and-Range. In the former, gravity data can be collected for interpretation in both detailed and regional projects, whereas in the latter, gravity surveys are generally limited to a more regional scale. Leveling remains a major obstacle to regional applications, but this may change with the now available GPS location control systems.

In their many variants, the electrical and electromagnetic methods are probably the most commonly used geophysical prospecting tools in both Great Basin and Archean environments. Scale of the surface arrays and the depth of investigation may be vastly different in the epithermal, polymetallic, and porphyry environments. Different techniques and methods have quite different applications and interpretation capability. Broadband IP/resistivity systems, with telluric cancellation, are feasible and again are being reviewed for deep prospecting through conductive overburden. TEM and CSAMT methods have become common in the Great Basin and will have increased application in shield terrains. The Singram method with increased separations and range of frequencies is useful and has application in the deeper till-covered areas. Technology and instrumentation for these methods continue to develop through increasing sensitivity, decreasing size, and utilization of multiple channels. The real change is in the on-going development of sophisticated software for data processing and reduction, and modeling and interpretation. Two-dimensional modeling is available and three-D is reported available on the larger computers. Airborne EM with high-sensitivity, multiple coils is routine. Output products are many and varied.

Seismic methods for exploration purposes produce mixed results in the Great Basin Paleozoic gold environments. Direct use is limited, but costly, in some terrains. Use of both refraction and particularly high-resolution shallow reflection methods has increased. However, much of the work is directed at overburden studies. Borehole logging and in-situ physical property measurements continue to be an important, but seldom utilized, evaluation approach.

Interpretation is trending away from the old anomaly-finding, black-box approach to a more quantitative geologically based evaluation. Modeling software and the variety of the calculated profile and map products have increased interpretation potential and efficiency. Seismic and electrical tomography, physical property studies, and evaluation of the more subtle anomalies are in the vanguard of exploration techniques. Research and development are currently being directed toward the relatively shallow environmental and engineering problems. Ultimately the ambiguity of potential methods and the equivalence problems of electrical methods will be reduced by better geologic control and a better understanding of the lateral and vertical range of physical properties. Multiple methods and techniques, together with the evaluation of the more subtle anomalous features, will lead to more discoveries.

Some concern is voiced about the "training" of future geophysicists and/or interpreters. Training, in this context, includes an academic degree, on-the-job experience, meetings and technical seminars, and formal in-house programs.

In the future, multiple methods will be applied to evaluate the more subtle anomalies both near the surface and at depth in difficult environments. Regional magnetics and gravity will be used to modify geologic maps in covered areas and to trace lithology and structure in the third dimension. The data need to be made available not only as maps, but also in floppy disk format of smaller areal blocks (e.g. 1° x 2°) for use by the smaller independent exploration companies.

GEOLOGICAL APPLICATIONS OF AIRBORNE GAMMA-RAY SPECTROMETRY

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Airborne gamma-ray spectrometry (AGRS) is an effective method of mapping ground level K, U, and Th from the air. It is a physical technique which can provide quantitative information about the distribution of any gamma emitting radioelements (natural or man-made) present on the land surface. For geological purposes data are reported as per cent K, ppm eU, and ppm eTh. Uranium exploration is only one geological application of the method. The geochemical properties of K, U, and Th are such that their absolute and relative concentrations can be used to discriminate between rock types and can be sensitive indicators of hydrothermal alteration. In siliceous magmas there is, in general, a steady increase in K, U, and Th with increasing SiO_2. In late-stage water-rich magmas and hydrothermal solutions, radioelement ratios change rapidly and distinctively. In the low-temperature sedimentary cycle there can also be a marked separation of U and Th, which is again readily indicated by ratio measurements.

It should be recognized that AGRS, like most other forms of exploration geochemistry, is primarily a soil or overburden mapping technique. Where overburden is related to the composition of bedrock in the vicinity, then the technique reflects the composition of bedrock; if overburden is not related, then the method maps changes in overburden and nothing more.

Development of AGRS as a mapping method commenced in Canada 25 years ago. There was serious concern that limited depth of penetration (approx. 0.5 m) would make the method ineffective for bedrock mapping and exploration in areas lacking extensive outcrops, and this was a subject of much initial research. In practice, as demonstrated by surveys now covering 45 per cent of the Canadian Shield, the limited penetration has proved to be less of a problem than was originally anticipated. Over much of the Shield the composition of the surface layer relates to bedrock in the vicinity; dispersion from a source of small dimensions can be used to advantage in exploration, given the sensitivity of the detection method. In those areas which are totally blanketed by thick till sheets and lake clays, AGRS provides a method of mapping the distribution of Quaternary formations, identifying till islands in lake clays, etc. As with all techniques, it is prudent to carry out AGRS interpretation in conjunction with complementary types of information.

For bedrock mapping the method can provide effective delineation of mixed lithologies, and is particularly effective at subdividing granitic and gneissic terrains. For the reasons indicated above, the method can outline important mineralized environments, such as carbonatites, peralkaline intrusives, late stage granites, volcanic ring complexes, pegmatites, ultrabasics, zones of K addition or removal, and zones of U and/or Th enrichment. With suitable equipment and survey specifications it is possible to use AGRS to distinguish zones a few hundred meters in width where the mean surface concentration contrast with the surroundings is of the order of 0.5% K, or 0.5 ppm eU, or 1 ppm eTh. The introduction of computer-plotted color maps over the past decade has greatly facilitated the presentation of these data. AGRS can assist in the discovery of many non-radioactive mineral deposits, e.g. Sn, W, REE, Nb, Zr, and less commonly Au, Ag, Hg, Co, Ni, Bi, Cu, Mo, Pb, and Zn.

Other applications of AGRS, which can be performed by a high-sensitivity system, include environmental radiation baseline studies, snow-water depth measurement, and fallout mapping in a nuclear emergency. As a standardized technique which is applicable worldwide over any type of land surface, AGRS can be used for levelling and correlating more conventional types of multielement geochemical survey, provided they include K, U, and Th data. This is of importance for future inter-regional and international geochemical map compilation purposes.

The USA is fortunate in possessing almost complete systematic AGRS reconnaissance data, gathered under the NURE Program in the late 1970s, recently edited by J.S. Duval of the USGS and shortly to be made available in CD-ROM format. This includes coverage for Minnesota.

APPLICATIONS OF NEAR-SURFACE GEOPHYSICS IN MINNESOTA

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"Near-surface geophysics" is a direct outgrowth of what used to be called "engineering geophysics." High-resolution methods aimed at targets within 200 feet of the surface have found increased usefulness in recent years in environmental, ground-water, geotechnical, and archaeological studies, as well as aspects of mining and oil exploration. The common need in these varied applications for detailed information about the near-surface requires similar geophysical approaches, despite different geological objectives.

The focus of this conference is the role of geophysics at the Minnesota Geological Survey (MGS). Being a publicly funded agency, it is important for the MGS to restrict its activities to those which are in the general public interest. The aeromagnetic program is an example of government-sponsored research which has produced tangible benefits for the state, through a project which would not have been undertaken by the private sector. The MGS downhole logging program, on the other hand, has in numerous cases provided benefits to very narrow interests by performing services for drillers who would otherwise have employed private logging firms. A great deal of valuable geophysical work can and should be done at the MGS, without infringing on the business of private concerns.

The greatest level of near-surface geophysical activity is currently in the environmental industry. Methods commonly used include electromagnetic induction (EM), seismic refraction and reflection, magnetometry, resistivity, gravity, and downhole logging. Unfortunately, many investigations are performed by people with inadequate training using "black box" style equipment. The MGS can assume an active role in better defining the uses of various methods by conducting research on well-constrained environmental sites.

Ground-water exploration is a traditional application of near-surface geophysics. Galvanic resistivity is the most commonly used method, but a number of other techniques are increasingly used, including seismic, EM, and downhole logging. Time-domain (TDEM) and very low frequency (VLF-EM) electromagnetic methods are used in some areas, but are not yet common in Minnesota. As in environmental work, ground-water geophysical surveys are often performed by those with little training, using discredited interpretation techniques. And a lack of information on geophysical characteristics of aquifers around the state hampers conscientious practitioners. The MGS can be of tremendous help by compiling information on aquifer characteristics, and by conducting research on the suitability of various methods for defining ground-water potential.

Geotechnical applications use a wide variety of geophysical methods, including seismic, ground-penetrating radar (GPR), cross-hole seismic, resistivity, gravity, and downhole logging. Geotechnical targets are usually highly specific, and less dependent on broad scale geological research than other areas. Still, MGS research on other applications of near-surface methods might well be fruitful in geotechnical work as well.

Geophysics plays a significant role in many archaeological investigations. Resistivity and magnetometry are the most widely used techniques, with GPR and EM becoming increasingly common. There seems to be a lack of communication between the geophysical and archaeological communities, however, resulting in a slow filtration of ideas between the two fields. The MGS can help in this area by maintaining contact with the state archaeologist, and conducting cooperative research into new geophysical applications.

The mining industry, while very familiar with most of the methods discussed, could benefit from recent advances in high-resolution seismic reflection, which can define shallow targets such as fault zones, bedrock channels, and other structural features important to mining exploration. Perhaps the most difficult obstacle to mining activity over much of Minnesota is the ubiquitous glacial drift covering potential exploration targets. An MGS seismic program could spur additional mining exploration by locating areas of relatively thin drift cover and identifying fault zones and other structural features.

While high-resolution seismic work is important in oil exploration, there have been, to date, no significant discoveries of oil or gas in Minnesota. Still, there is interest in the oil potential of Paleozoic sediments flanking the Midcontinent rift system, including at least one exploratory well in Iowa. If oil prices increase, there will likely be a certain amount of petroleum exploration in the state in the next decade. The MGS would then have an important function in overseeing oil-related geophysical activity.

In light of the above discussion, I am recommending four specific projects for the MGS to consider:

1) Geophysical mapping of bedrock in northern Minnesota and other areas with mining potential, to locate areas with relatively thin drift cover, map fault zones, alluvial channels, and other structural features of interest. This would be a coordinated program of seismic reflection, seismic refraction, resistivity, EM, drilling and downhole logging, as well as utilizing the existing aeromagnetic data base.
2) Develop a data base of geophysical properties of Minnesota formations, including such parameters as acoustic velocity, resistivity, chargeability, density, and magnetic properties. This would involve a combination of field surveys, laboratory testing, downhole logging, and compilation of data from various outside sources.
3) Conduct applied research into new applications of existing geophysical methods, such as IP, azimuthal resistivity, TDEM and VLF-EM, vertical seismic profiling, and seismic tomography. Commonly used methods could be tested to better document their effectiveness and limitations in various environments.
4) Work more closely with other MGS personnel to provide geophysical support for ongoing projects, such as county atlases and ground-water research. Consolidation of downhole and surface geophysics into a single group would facilitate this effort.

INNOVATIONS IN THE INTERPRETATION OF REGIONAL MAGNETIC, GRAVITY, AND AIRBORNE ELECTROMAGNETIC DATA

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The Branch of Geophysics at the U. S. Geological Survey has developed innovative methods for interpreting regional gravity and magnetic maps in recent years. This abstract summarizes the methods that have application to the geologic terranes of Minnesota. The methods, all of which transform data to produce interpretive maps, range from those routinely applied by the Branch, to those newly generated and yet unpublished, to one that is still in development. The data sets addressed by each method vary, but may include gravity, magnetic, airborne electromagnetic (in the form of apparent resistivity) data, or a combination of these.

The horizontal gradient method, which is now routinely used by the Branch of Geophysics, estimates the locations of physical-property boundaries that commonly occur at geologic contacts (Cordell, 1979; Cordell and Grauch, 1985; Blakely and Simpson, 1986). These locations are estimated by local maxima of the magnitude of the horizontal gradient of the gravity, pseudogravity, or resistivity data. The maxima locate where the data values change most rapidly. Recently, the horizontal gradient method, which estimates the edges of sources, has been extended by the terrace method (Cordell and McCafferty, 1989), which then assigns a physical-property value to each source for gravity and magnetic data. The terrace method is similar in purpose to apparent susceptibility methods, but is faster and designed to yield discrete rather than continuous map areas; this corresponds more closely to geologic maps.

A method developed to separate the gravity effects of basins from those of basement in the Basin and Range (Jachens and Moring, 1990) may be of service in separating bedrock gravity effects from those of glacial till in Minnesota. The separation in the Basin and Range was accomplished through iterative adjustment of a regional field that was initially computed from gravity stations located exclusively on basement. The final regional field represents basement effects, and the complementary residual field represents basin effects. This method may have regional application in Minnesota where gravity stations on bedrock outcrops are not too far apart compared to total gravity station coverage.

Several methods have been developed that combine information from more that one geophysical data set. One such method displays gravity and magnetic data, and the ratio between the two as a color composite of three colors (Phillips, 1990). In an area in southwestern Maine, this enhanced the differences between granitic, mafic, and metasedimentary rocks. Another method computes a correlation coefficient between two data sets within a moving window. In areas where correlations between data sets are insignificant, a damping factor may be selectively applied to suppress the correlation coefficient (Grauch, 1987). Another method that combines magnetic and apparent resistivity information multiplies the log of the horizontal-gradient magnitude of reduced-to-pole magnetic data by the log of apparent resistivity. In an area of north-central Nevada, results of this multiplication helped discriminate igneous rocks from well-consolidated sedimentary rocks. It may be possible to combine geophysical data sets in this way (or a similar way) to discriminate bedrock lithologies in Minnesota.

A final method, still under development, determines where a gradient trend of a geophysical map exists within a moving window and plots that trend as a color determined by the trend direction (Grauch, 1989). The resulting display shows where linear trends of anomalies or the edges of anomalies are statistically justified. This technique is more objective than the common approach of determining such trends by eye. This method cannot presently handle areas having more than one trend direction; this is the focus of further development.

Blakely, R. J., and Simpson, R. W., 1986, Locating edges of source bodies from magnetic or gravity anomalies: Geophysics, v. 51, p. 1494-1498.

Cordell, Lindrith, 1979, Gravimetric expression of graben faulting in Santa Fe country and the Espanola Basin, New Mexico: New Mexico Geol. Soc. Guidebook, 30th Field Conference, Santa Fe, p. 59-64.

Cordell, Lindrith, and Grauch, V. J. S., 1985, Mapping basement magnetization zones from aeromagnetic data in the San Juan Basin, New Mexico, *in* Hinze, W. J., ed., The utility of regional gravity and magnetic anomaly maps: Tulsa, Society of Exploration Geophysicists, p. 181-197.

Cordell, Lindrith, and McCafferty, A. E., 1989, A terracing operator for physical property mapping with potential field data: Geophysics, v. 54, no. 5, p. 621-634.

Grauch, V. J. S., 1987, A new variable-magnetization terrain correction method for aeromagnetic data: Geophysics, v. 52, no. 1, p. 94-107.

Grauch, V. J. S., 1989, Statistical examination of linear trends in a compilation of aeromagnetic data from the southwestern U. S.: Society of Exploration Geophysicists Expanded Abstracts with Biographies, 59th Annual International SEG meeting, v. 1, p. 351-352.

Jachens, R. C., and Moring, B. C., 1990, Maps of the thickness of Cenozoic deposits and the isostatic residual gravity over basement for Nevada: U. S. Geological Survey Open-File Report 90-404, 15 p., 2 pl.

Phillips, J. D., 1990, Integration of potential-field and digital geologic data for two North American geoscience transects: Journal of Geological Education, v. 38, p. 330-338.

DIVERSE SEISMIC REFLECTION IMAGES FROM THE CANADIAN SHIELD

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In most reviews of deep seismic reflection results, Precambrian shields are portrayed by a single model that has a complexly reflective upper crust overlying a largely non-reflective lower crust and a poorly defined reflection Moho. This simple viewpoint, which is based on the limited seismic reflection data available from Precambrian shields up until the mid-1980s, is being revised on the basis of results from more recent surveys. Since 1986, GLIMPCE and LITHOPROBE have collected or purchased nearly 5000 km of seismic reflection data from a wide variety of structures on the Canadian Shield. An additional 1000 km of data collection is planned in 1991. Targets surveyed or to be addressed include:

(1) the Abitibi Belt (surveys in 1987/1990), an Archean greenstone terrane that involved island arc and rift-type volcanism and juxtaposition of volcanic and sedimentary units in zones of oblique convergence;
(2) the Kapuskasing Structure (1987), interpreted as a partial cross section of Archean crust that was thrust to the surface during the early Proterozoic;
(3) the Penokean and Trans-Hudson Orogens (1986/1991), continental-scale fold belts of early Proterozoic age that contain the vestiges of Proterozoic island arcs and Archean micro-continents welded to the margins of the Archean Superior craton;
(4) the Grenville Orogen (1986/1991), a huge tract of high-grade metamorphic rock that extends the length of North America, interpreted to represent the middle and lower crust of a Himalayan-type mountain belt of middle Proterozoic age;
(5) the Midcontinent Rift System (1986), a middle Proterozoic rift that almost ruptured the North American continent;
(6) the Sudbury Eruptive (1990), a possible impact structure of Early Proterozoic age.

Seismic sections obtained from these structures are highly variable. They include images of gently dipping thrust faults and steeply dipping strike-slip faults in the Abitibi Belt, listric thrust faults and reflective upthrust lower crustal rocks in the Kapuskasing Structure, a subhorizontal decollement (Lake Huron) and a major crustal root (Lake Michigan) beneath the Penokean Orogen, anastomosing ductile shear zones that penetrate the entire crust within the Grenville Orogen, and giant asymmetric and symmetric grabens of the Midcontinent Rift System. From the large and growing data base available from the ancient shields, we conclude that Precambrian crustal sections are as structurally diverse as their Phanerozoic counterparts and that many can be explained by modern plate tectonic concepts.

GEOPHYSICS AND THE GEOLOGIC MAPPING MISSION OF THE MINNESOTA GEOLOGICAL SURVEY

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The Minnesota Geological Survey and Natural History Survey was organized in 1872 as a unit of the University of Minnesota. In the early days the staff consisted of a geologist, a chemist, a topographer, an ornithologist, an entomologist and a laboratory assistant—an interdisciplinary scientific team that covered rocks, the birds and the bees (actually the mosquitoes!). Even though no particular staff member had the title of geophysicist, the discipline of geophysics soon became important in the Minnesota Geological Survey, because the magnetic properties of iron ore made magnetic methods essential for mineral exploration in the drift-covered terrain of the state.

Although today's Quaternary geologists like to call bedrock the "underburden," the fact that 90 percent of Minnesota's bedrock is obscured by glacial deposits resulted in the Minnesota Geological Survey taking an early leadership position in using geophysics in geologic mapping. For example, in 1947, Professor George Schwartz, director of the Minnesota Geological Survey, signed a cooperative agreement with the U. S. Geological Survey to begin an aeromagnetic survey, one of the first in the nation. This work from 1947 to 1952 resulted in coverage of 40,000 square miles of the northern part of the state. In 1965, during the tenure of Paul Sims as director, MGS started a gravity mapping program at a scale of 1:250,000. For the occasion of the 100th anniversary of the Survey in 1972, Sims produced a new geologic map of the state at a scale of 1:1,000,000. This map represented one of the first attempts in the United States to use aeromagnetic and gravity data systematically to interpret bedrock geology beneath extensive drift-covered areas.

In the 1970s, geophysics at the Minnesota Survey really took off under the remarkable leadership of Matt Walton as director, and with the tremendous support of the Legislative Commission on Minnesota Resources and its executive director Bob Hansen. The new LCMR high-resolution aeromagnetic survey of Minnesota began in 1979, funded by revenues from the state cigarette tax and pursuant to scientific recommendations of an international workshop convened to advise the state—in fact, that earlier workshop was the predecessor and the inspiration for this year's event.

Bob Hansen has especially asked me to convey to you his special greetings, and he is very sorry that a previous commitment in Washington has prevented his attending our workshop. Suffice it to say that without Matt's leadership, Bob's encouragement and active support, and the Commission's allocation of the needed funds, the MGS aeromagnetic survey would not have been possible. Furthermore, the continuous financial support provided by the Commission enabled MGS to employ Val Chandler as project manager from start to finish, and Val exemplary performance in maintaining vendor quality control, keeping products on schedule, and producing numerous scientific publications in peer-reviewed journals in the meantime is an outstanding achievement.

The mission of the Minnesota Geological Survey is to undertake and promote the scientific study of Minnesota's geology, ground water, and mineral resources, and to make the results readily accessible to the public. As a unit of the University of Minnesota, MGS participates in all three functions of a land-grant university: research, service, and teaching. As a university research center, MGS differs substantially from state geological surveys that are government agencies. We have professors and students on the staff in addition to civil service employees; we have no regulatory role; and our work includes basic earth sciences research and teaching about Minnesota geology that may have no immediately apparent practical applications. In Minnesota there are other entities that carry out activities that are assigned to state geological surveys elsewhere. For example, the Minnesota Department of Natural Resources has a Division of Minerals responsible for mineral leasing and associated regulatory and mineral resources assessment activities, and a Division of Waters responsible for ground-water allocation and issues of ground-water supply. The Minnesota Department of Health and the Pollution Control Agency have state responsibilities in the area of water quality. The University's Mineral Resources Research Center and Natural Resources Research Institute are actively engaged in applied research on mineral resources and mineral processing, taconite and peat, and cooperative programs involving industry. Also, in contrast to some geological surveys outside the United States, MGS focuses on studies at the regional level rather than the more intensive site-specific exploration and geotechnical investigations that are conducted by the private sector in Minnesota.

The central activity pursuant to our mission is geologic mapping. When I say geologic mapping, I mean the term in the broadest sense—development of a sophisticated information base that delineates the three-dimensional geologic framework of the state, including the associated interpretation of geologic processes and crustal evolution in time.

Consistent with our land-grant mission, geologic maps produced by MGS are the primary data base for virtually all applied and basic earth science research, service and teaching devoted to Minnesota geology. They are necessary for user groups involved in the exploration and development of water and mineral resources; in land-use evaluation and planning for development and preservation of environmental quality; in the siting and construction of infrastructure such as transportation corridors and waste disposal facilities. Geologic maps are also essential for scientists studying the structure and evolution of earth materials and the processes that formed them; and recognition, assessment and mitigation of earth hazards such as earthquakes and sinkholes.

Minnesota presents special challenges for geologic mapping: an unusually long and complex geologic record stretching back over 3.5 billion years; extensive, and in places, exceptionally thick glacial cover; and a remarkably intricate Quaternary stratigraphy, the product of repeated advances and retreats of continental glaciers. We face this mapping challenge in a state societal environment of rapid population growth, active urban expansion, accelerated ground-water withdrawals, substantial threats to ground-water quality, and increased economic demand for mineral exploration and development—all these factors press for more and better geologic maps for Minnesota. In the meantime, our state like others faces difficult budget times ahead, so every state dollar spent in geologic mapping is going to have to be more productive than ever before. The drive for higher productivity means we have to work smarter—and geophysics is the key.

USE OF PALEOMAGNETISM IN PRECAMBRIAN TERRANES

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Due to their long and involved history, Precambrian rocks often have a complex paleomagnetic signature involving one or more imprints superimposed on any surviving primary remanence. The interpretation of paleomagnetic data from Precambrian rocks can therefore be particularly challenging and has led to the development of several analytical methods for component separation (e.g. Halls, 1978; Kirschvink, 1980).

The paleomagnetic method has been applied successfully in Minnesota to unmetamorphosed basaltic rocks, such as the 1.1 Ga Keweenawan North Shore volcanics and feeder dykes (Green et al., 1987; Books, 1972; Halls and Pensonen, 1982) and the 2.1 Ga Kenora-Kabetogama (KK) dyke swarm (Halls, 1986). The former study is an excellent example of the use of paleomagnetism as a correlation tool, where a magnetic polarity reversal has helped to correlate the Minnesota sequence with others around Lake Superior. Both studies highlight a second use for the paleomagnetic method—the establishment of a reliable Precambrian Apparent Polar Wander (APW) path for North America for which remanences are precisely dated and defined in direction. The large areal extent of the KK dykes and the consistency of paleomagnetic directions both across the swarm and along individual dykes ensures that the remanence is primary and has not been significantly tilted. Precise U-Pb age dates are now possible for basaltic rocks and several swarms have now been dated (e.g. Krogh et al., 1987; LeCheminant and Heaman, 1989). They constitute some of the firmest tie points on the Precambrian APW path. Relatively fresh basaltic dykes and intrusions of largely unknown age occur in the Minnesota River Valley and represent potential targets that may add reliable data to the APW path.

A relatively new application of paleomagnetism in shield areas is in the definition of regional uplift and deformation of supposedly stable cratons such as the Superior Province. Two methods are available and both utilize dykes. The first examines both the dyke and its zone of totally and partially reheated rocks. Assuming a value for the geothermal gradient, it is possible to estimate the amount of crustal uplift and erosion since the dyke was emplaced (Buchan and Schwartz, 1987). In theory the rate of uplift, particularly in the southern Superior Province, can be estimated because several ages of Proterozoic dykes are present.

In the second method the attitude and paleomagnetic direction of individual dykes is obtained for a large swarm, and any regional changes in paleomagnetic direction of individual dykes, particularly if correlated with changes in dyke orientation, can be interpreted in terms of crustal rotation subsequent to intrusion. This type of study has been successful for the 2.45 Ga Matachewan dykes (Halls and Shaw, 1988; Halls and Palmer, 1990; Bates and Halls, 1990). Detailed studies on crosscutting dykes of this swarm suggest that only one reversal of the earth's magnetic field, from "reversed" R to "normal" N polarity, took place during the time the swarm evolved (Halls, in review). The polarity of a dyke is thus an immediate chronometer in terms of whether the dyke was formed early or late in the intrusive episode. The dominant polarity of the dykes changes both along and across the swarm, the boundary between these polarity domains being formed by faults associated with the Kapuskasing Structural Zone (KSZ), across which vertical displacements of several kilometers have taken place. Those areas of the swarm which have been relatively uplifted have a dominant N polarity, are mineralogically much fresher, and have peculiar tea-colored feldspars (Halls and Palmer, 1990). The appearance of these dykes is a reflection of their greater depth of emplacement. Their normal polarity may be primary (in which case younger dykes tend to be deeper), or a product of delayed cooling (i.e. the dyke was intruded in an R field but did not acquire its remanence until after the field had reversed). The overall shape of the swarm is that of a fan; the radial disposition is intact south of the KSZ but becomes distorted into a Z-shaped pattern across and to the north of the KSZ. In this region the remanence declination is strongly correlated with dyke trend suggesting that the swarm has suffered a major distortion subsequent to its emplacement, involving differential rotations of up to 40° along a strike length of several hundred kilometers (Bates and Halls, in review). South of the KSZ the remanence direction is the same despite differences in the regional trend of the swarm, suggesting that the radial pattern here has remained unchanged. Both the differential uplift and crustal rotation are contemporaneous with the evolution of the KSZ, the main phase of which is estimated at about 1.95 Ga. Two main conclusions of this work are that the Matachewan swarm was at one time almost perfectly radial, and secondly that Archean shields can undergo significant internal deformation as a result of early Proterozoic collisional events taking place around their margins. The impact of an orogen on a craton depends upon the extent of continental collision and the obliquity of the collision. Following burke (1983), the Kapuskasing Zone and the wider deformation revealed by the paleomagnetic data are the product of ESE-directed stress associated with the Hudson Orogen.

In most orogenic belts the rocks have been sufficiently metamorphosed and deformed that any primary remanence has been completely destroyed. Remanences that do survive are those which are related to the final uplift and cooling of the orogen. Examples of uplift-related remanences are those from the Grenville Province (Hyodo et al., 1986). Sometimes it may be possible to identify remanences that are formed at different stages of uplift and these can be dated by the Ar-Ar method on minerals of different closure temperatures. The rocks which respond best to this method are generally high-grade gneisses and tonalites; the McGrath Gneiss and related bodies in Minnesota, for example, may be suitable targets for this type of study.

A final challenge for paleomagnetism, with possible applications to Minnesota, is to define the extent and age of zones and areas of secondary magnetization in the shield. These secondary events may reflect heating by late intrusions, reactivation of faults, or episodes of major fluid migration and chemical alteration associated with neighboring orogenic belts, or with intrusive or metamorphic events taking place at depth. The study of fluid-generated remanences is particularly difficult because the low temperatures involved do not favour the formation of stable remanences. However the results are important to the question of how fluids migrate in the crust and whether areas can be defined which have remained relatively dry. West of the Kapuskasing Zone, an area of anomalously weak aeromagnetic expression contains Matachewan dykes that have been reset magnetically (Bates and Halls, in review), an unusual feature in a swarm where primary remanences are the rule. A similar aeromagnetically anomalous region, attributed to alteration, forms the fold and thrust belt of the Penokean orogen in Minnesota (Southwick et al., 1988). The origin of these altered areas is problematical but in view of possible economic implications should be investigated in more detail.

REFERENCES

Bates, M.P. and Halls, H.C., 1990. Canadian Journal of Earth Sciences 27, p.200.
Bates, M.P., and Halls, H.C., In review to Canadian Journal of Earth Sciences
Books, K., 1972, U.S. Geological Survey Professional Paper 760, 42 p.

Buchan, K.L., and Schwartz, E.J., 1987. Geological Association of Canada Special Paper 34, p. 221.
Burke, K., 1983. Lunar Planetary Institute Technical Report No. 83-03, p. 20.
Green, J.C., & 6 Authors, 1987. Geological Association of Canada Special Paper 34, p. 289.
Halls, H.C., 1986. Canadian Journal of Earth Sciences, 23, p. 142
Halls, H.C., In review to Earth and Planetary Science Letters.
Halls, H.C., and Palmer, H.C., 1990, Canadian Journal of Earth Sciences, 27, p. 87.
Halls, H.C., and Pesonen, L.J., 1982. GSA Memoir 156, p. 172
Halls, H.C., and Shaw, E.G., 1988. Canadian Journal of Earth Sciences, 25, p. 732.
Hyodo, H., Dunlop, D.J., and McWilliams, M.O., 1986, Geological Association of Canada Special Paper 31, p. 119.
Kirschvink, J.L., 1980. Geophysical Journal, Royal Astronomical Society, 62, p. 699.
Krogh, T.E., and 8 Authors, 1987. Geological Association of Canada Special Paper 34, p. 147.
LeCheminant, A.N., and Heaman, L.M., 1989. Earth and Planetary Science Letters, 96, p. 38.
Southwick, D.L., Morey, G.B., and McSwiggen, P.L., 1988. Minnesota Geological Survey Report of Investigations 37.

FLUID DETECTION USING ELECTROMAGNETIC GEOPHYSICS

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The detection and monitoring of acid leachate (lixiviant) during in situ leach mining processes is necessary for the protection of aquifers or groundwater reservoirs and for the economic viability of the mine. The Bureau of Mines, therefore, conducted research on electromagnetic geophysical methods that might be used to map the horizontal or vertical extent, and monitor the progress of leachate plumes.

In order to address the problem of lixiviant detection, the Bureau of Mines conducted a field experiment in which several electromagnetic techniques were tested for their ability to detect the presence of a brine solution. In the controlled experiment, 29,000 gallons of water containing 23 g/l sodium chloride was injected into one and, later, two boreholes over an 8-day period to produce a high-conductivity plume. This created a conductivity contrast of more than two orders of magnitude between the country rock and the brine solution.

Six surface or borehole methods, including surface controlled source audio-frequency magnetotellurics (CSAMT), time-domain electromagnetics (TEM) and magnetic ellipticity, surface-to-borehole FEM and TEM, and cross-borehole EM, were tested both before and during the injection of brine. Pre-injection data were used for comparison against during-injection data to reduce geologic noise and isolate the brine's response. All methods were successful to different extents in detecting the brine plume. However, the borehole methods provided greater sensitivity and were more diagnostic than the surface methods.

THE ROLE OF REGIONAL GEOPHYSICAL STUDIES IN THE MIDCONTINENT: NEW VIEWS ON AN ANCIENT RIFT

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Geophysical studies began in the Midcontinent as focused investigations of limited areas to solve specific geological objectives or mineral-resource exploration or assessment problems. During the past several decades these studies - gravity, magnetic, and seismic - through the leadership of the geoscience departments of the regional universities and the state geological surveys working in concert with federal agencies were expanded to cover extensive regions, but generally with limited detail and precision. The objective of these 'regional' surveys was to map the gross structure, composition and nature of the crust and the upper mantle and, therefore, to assist in interpreting the geological evolution of the region. Most geoscientists understand that this information is absolutely critical to evaluating and stimulating the exploitation of earth resources and investigating a broad range of earth science-related societal problems such as earthquake hazard assessment and storage of hazardous wastes. Unfortunately, direct geologic information from outcrops and drill holes is too sparse and provides an insufficient view of the earth's vertical dimension for proper analysis. Thus geophysical methods which provide an indirect view of the earth's third dimension are absolutely essential. However, interpretation of these geophysical data remains highly subjective. This limitation can be controlled through the synergistic interpretation of data obtained from a variety of geophysical methods constrained by available geologic information. In the Midcontinent the amount and quality of geologic information on the crystalline basement rocks are limited because of sparse exposures and poor distribution of drill holes. Limited drill holes (and essentially none of those over a kilometer in depth) are positioned to solve scientific problems, but rather are located for mineral resource evaluation. The situation in the northern Midcontinent, fringing the southern perimeter of the Precambrian Shield, is less bleak because geophysical investigations are particularly successful where they are constrained by extrapolation from directly observed structures and lithologies in the outcrop. Such is the case, for example, for the Great Lakes tectonic zone and the Midcontinent Rift System.

Regional geophysical studies are used in the Midcontinent (1) to determine the configuration of the basement beneath the surface Phanerozoic sedimentary rocks and the glacial sediments and residual soils, (2) to map the structure and lithology of the basement rocks leading to understanding the paleotectonics of the crust, and (3) to investigate the tectonics and structure of the Phanerozoic sedimentary rocks. In the latter case the objectives are to determine the origin of vertical movements and related Phanerozoic sedimentary depositional patterns, to ascertain the origin of Phanerozoic structural features, to provide structural information related to fluid flow in Phanerozoic rocks, and to map seismicity zones. Unfortunately, the levels of detail and precision of the regional data are insufficient to adequately investigate the upper crust, particularly the very important top few kilometers of the crust. The gravity stations are too widely separated and elevation control is limited, the aeromagnetic surveying is insufficiently dense and at too high elevations, and the seismic data are limited by both shot and receiver density.

Fortunately, regional geophysical studies in the Midcontinent have moved into a new stage over the past decade. In this stage, data are obtained in a relatively consistent manner over broad regions in much greater detail and higher precision than hitherto available. These high-resolution regional data are opening up important new opportunities for improved quantitative analysis, inversion, and presentation of the fine structure of the upper crust. These types of data are available only for limited areas of the Midcontinent. Examples are the high-resolution aeromagnetic survey of Minnesota, the GLIMPCE deeply penetrating reflection and wide-angle seismic studies in Lake Superior, the new high-resolution magnetic survey of Lake Superior, and the mid-crustal depth reflection seismic data being made available to the scientific community by geophysical contractors and petroleum exploration companies.

The impact of these new high-resolution regional data has been particularly profound on our understanding of the Proterozoic Midcontinent Rift System (MCR). The MCR extends from southern Kansas to Minnesota, Wisconsin, Michigan, and adjacent portions of Canada where it crops out and then trends southeast across the Southern Peninsula of Michigan for a length in excess of 2000 km. Arguably, it is the most significant anorogenic feature of the Midcontinent. The mafic extrusive and intrusive rocks, as well as the associated clastic rocks of the rift, contain important concentrations of base and precious metals, and petroliferous clastic rocks occur within the rift opening the possibility of hydrocarbon deposits. Also, the permeable clastic rocks are a significant hydrologic unit. Rift-related crustal-weakness zones have been reactivated repeatedly by prevailing stresses over the past 1100 Ma, controlling structures and lithofacies variations within the overlying Phanerozoic sedimentary rocks, as well as seismicity. Analysis and interpretation of the high-resolution regional geophysical data, together with studies of the isotopic systematics of the volcanic rocks, have ushered in a new era of understanding of the MCR. Ideas expressed a decade ago as speculation have developed into credible hypotheses. The rift origin of the feature now seems universally accepted, as is the recognition of a late-stage compressional event that caused the original normal faults to be reactivated as high-angle reverse faults with as much as 5 km of vertical uplift. We now accept vertical accumulations of as much as 20 km of volcanic rocks and 10 km of clastic sediments. Furthermore, it appears that there is a commonality in the structure and age of the rift over its entire length. Moreover, the rifting event had a profound effect upon the entire crust. The rift is now generally associated with a Keweenawan thermal event - a hotspot - leading to an essentially complete rupture of the crust and extrusion and intrusion of over a million cubic kilometers of mantle-derived mafic rocks onto and into the crust. The nearby, contemporaneous Grenville orogenic event likely had an important impact upon the evolution of the rift. Stresses associated with the orogeny may be the source of the late-stage compression of the rift. These advances in our knowledge of the rift structure and its related rocks and refinement of our hypotheses regarding the tectonic evolution mark a significant improvement over the situation of a decade ago. However, this improvement has focused our attention upon more specific and detailed questions about the nature and evolution of the rift, such as the amount of extension of the crust over its entire length, the nature of the modification of the lower crust and the role of crustal underplating, the significance of transitional stresses and related crustal movements, the possible presence of evaporites within the sedimentary section, and the history of marginal and regional uplift associated with the rifting process. The improved synergistic analysis and interpretation of the available high-resolution geophysical data together with geologic information, and the acquisition of more extensive high-resolution geophysical data, as well as focused detailed data, will have an important role in searching out the answers to this new generation of questions related to the MCR and other crustal features of the Midcontinent.

AEROMAGNETIC SURVEYING: PRESENT AND FUTURE PERSPECTIVES

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In recent years, improvements to the aeromagnetic survey techniques have occurred in both the instrumentation, namely in optical absorption magnetometers, compensation and data-acquisition systems, and in the navigation of survey aircraft. Scintrex Ltd. of Concord, Ontario, have redesigned their cesium vapor magnetometers. The new CS-2 magnetometer has an increased working orientation range of $\pm$ 35° and the instrumental noise level is below 0.001 nT RMS. EG&G Geometrics of Sunnyvale, California has completed development of a metastable helium magnetometer that is based on Chinese technology. The single-cell G-833 magnetometer has an RMS noise level of 0.005 nT. The third notable magnetometer development has been by GEM Systems of Richmond Hill, Ontario, who have been fabricating an optically-pumped potassium magnetometer system using a basic sensor developed by the Vavilov Optical Institute in Leningrad, USSR. The GSMP 20 magnetometer utilizes a single narrow spectral line, so there is virtually no orientation error, and the Larmor frequency ratio is approximately 7Hz/nT, i.e., about twice that of cesium, so it is basically twice as sensitive.

For various reasons, optical absorption magnetometers have now largely replaced proton precession magnetometers for aeromagnetic surveys. The reasons include their higher sensitivity and sampling rate but especially the fact that the use of optical absorption magnetometers is now royalty free.

In order to utilize fully the higher sensitivities of the recent generation of optical absorption magnetometers, it is mandatory to employ active compensation systems that nullify the varying magnetic signals of the survey aircraft that are generated by air turbulence in flight. The resultant noise swath is superimposed on the geological signal and is generally proportional to the turbulence, and in turn to how well the survey aircraft is compensated. All the present active compensation systems utilize a set of orthogonal fluxgate elements that sense the magnetic changes caused by the aircraft. These changes are utilized to correct the measured total field values either by use of compensation coils close to the survey magnetometer or through software corrections to the total field values recorded. Using these systems, the compensation figure of merit (FOM) of aeromagnetic survey aircraft permit an FOM of 4 nT for regional aeromagnetic surveys and 1 nT for vertical gradiometer surveys to be specified. This has resulted in the noise swath as displayed by the fourth difference trace being less than 0.05 nT even at times of considerable turbulence, thus allowing high resolution surveying operations to continue.

After a long gestation period, the Global Navigation System (GPS) will now provide positions accurate to about 10 meters during daylight hours in most parts of the world, and so it can be relied upon as the prime navigation technique along with Doppler or INS (and with flight path camera backup) in aeromagnetic surveys, i.e., it is now an operational reality. As of November 1990, 14 satellites were operational in orbit with additional GPS satellites being launched approximately every 2 months.

GPS is having a number of beneficial effects to the practice of aeromagnetic surveying. First, surveys can be carried out in any part of the world to the same navigational accuracy whatever the terrain. Second, a much more even network of traverse and control lines can be flown using a left-right indicator mounted in the cockpit. Indeed pilots are flying without the benefit of topographic maps. Third, the flight path recovery process can be automated and a minimum of point picking is required, reducing the overall cost of aeromagnetic surveys especially for offshore surveys. Full deployment of GPS probably will also increase the overall use of the aeromagnetic survey technique, because featureless areas of the world can now be flown at the same cost as those flown elsewhere. Most of the airborne geophysical contractors are now utilizing GPS in their survey operations.

In Canada, a regional aeromagnetic program, which has been carried out for the past 43 years, now covers about 70% of the land area and a considerable portion of the surrounding continental shelves. The areas surveyed include the economically important greenstone belts of the Canadian Precambrian Shield which comprise about 25% of the Superior Structural Province and contain most of the mineral deposits. The aeromagnetic program has been credited with a prime role in a number of mineral discoveries in the shield and elsewhere in Canada. These include, in addition to the direct discovery of iron ore, a pathfinding role in the discovery of massive sulphide deposits of the base metals which often contain the magnetic mineral pyrhotite. In recent years, magnetic survey results have also been of great assistance in gold exploration programs, particularly in delineating the underlying geology in the vast drift-covered areas of the Canadian Shield which often have minimal outcrop. Alkaline syenite-carbonatite complexes which may contain niobium and tantalum mineralization are easily recognizable because they usually generate bulls-eye magnetic anomalies. On the continental shelf of eastern Canada, reconnaissance aeromagnetic surveys have successfully delineated areas underlain by sedimentary rock with hydrocarbon potential.

Aeromagnetic surveys have also been carried out by Canada in a number of developing countries, especially Africa, through funding provided by the Canadian International Development Agency (CIDA). Of particular interest is the aeromagnetic survey of Zimbabwe which was completed in January 1991. The results of the Zimbabwe survey demonstrate how well the greenstone belts where most of the gold mines are located (as is also the case in the Superior province of Canada) are delineated. The greenstone belts occur as areas of low magnetic relief often associated with local highs produced by iron formation. The greenstone belts are best seen on the colored magnetic anomaly maps in which the dominating effects of the earth's core field have been removed.

Vertical gradiometer techniques have been developed by GSC to provide more definitive aeromagnetic survey coverage to assist detailed geological mapping programs, e.g., 1:20,000 scale. The GSC initially built its own inboard fixed-wing system on a Beechcraft Queenair aircraft using optical absorption magnetometers in the early 1970s. A substantial experimental survey program was then carried out to demonstrate the efficacy of the gradiometer technique before a technology transfer was made to airborne survey contractors. More recently the GSC has fostered through R&D contracts the development of helicopter-borne towed-boom systems for use in mountainous terrain.

In a further development of the gradiometer technique, Anglo American Corp. of South Africa have sponsored the fabrication of a four-sensor airborne gradiometer system that measures the gradient in three orthogonal directions. The system must be the first three-axis gradiometer system to be built. It utilizes Scintrex strap-down H8 cesium sensors and an RMS Instruments AADC compensator installed on a Cessna 404 Titan survey aircraft. The triaxial gradiometer should be a very powerful exploration tool for diamond-bearing kimberlites in southern Africa.

INTERPRETATION OF NEW AIRBORNE GEOPHYSICAL DATA EFFIE-COON LAKE AREA, MINNESOTA

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New airborne geophysical instrumentation and data-processing methods developed by the U.S. Geological Survey (USGS) Branch of Geophysics were used to supplement standard airborne magnetic methods commonly used in regional subsurface mapping. The purpose of this study was to apply emerging technology in airborne geophysics and advanced data-processing methods to geological mapping of an area covered by glacial overburden.

The study area lies within a late Archean granite-greenstone bedrock which is more than 95% concealed by Quaternary glacial deposits that range to 100 meters thick. Within the study area, three large felsic plutons and a mafic sill complex (Deer Lake) have intruded the steeply dipping metasedimentary and metavolcanic country rocks which also host several thin iron-formations. A northwest-trending Early Proterozoic mafic dike swarm cuts the Archean terrane. Records of mineral exploration activities (Minnesota Department of Natural Resources) show that the Deer Lake Complex was previously explored for base-metal deposits. That exploration used detailed commercial airborne electrical and magnetic surveys (1/8-mile line spacing). Recent mineral exploration just to the east of the study area has identified gold mineralization associated with iron-formations like those in the southeastern part of the study area.

New USGS airborne data presented here include standard total magnetic field and USGS-developed electromagnetic (EM) Very Low Frequency (VLF) and powerline source instrumentation. The source for VLF signals is distant radio transmitters operating at about 20 kilohertz. The powerline system measures the electromagnetic fields radiating from powerlines at 60 Hz and harmonic frequencies of 180 and 300 Hz, and has a much greater depth of penetration than the VLF signals.

The new airborne magnetic data were processed to produce color shaded relief and first vertical derivative maps which enhance subtle bedrock geological features. Other analysis techniques were used to generate "maxspot" and "terrace" maps, which can be used to interpret boundaries of subsurface magnetic sources based on interpreted variations of magnetic susceptibility. This type of processing can enhance the variations of magnetic properties of iron-formations and thereby indicate structures or alteration zones that may be favorable for gold mineralization.

USGS data from the VLF and powerline EM systems were reduced to make maps showing apparent resistivity of the survey area. In this glaciated terrain, the VLF data generally reflect near-surface (tens of meters) features such as glacial deposits and shallow high-resistivity bedrock and are useful in interpretation of more deeply penetrating powerline airborne EM data. In the south-central part of the survey area, glacial eskers are associated with sinuous apparent resistivity highs. Low apparent resistivities in the northwest part of the survey area reflect thick glacio-lacustrine clay deposits that can attenuate the airborne powerline EM anomalies.

In contrast to the VLF measurements, the powerline EM system has a greater depth of penetration (hundreds of meters) and is less sensitive to the glacial overburden. Individual anomalies from the powerline system compare favorably with those mapped by the previous commercial airborne EM system. However, the anomalies from the powerline system suggest that the zones of low resistivity in the Deer Lake Complex extend farther to the southwest than mapped by the commercial EM systems.

Integrated interpretation of all the geophysical, geological, and geographical data was facilitated by using Geographic Information System (GIS) software. The GIS system can easily display various data sets as overlays to enhance their subtle features. For example, the magnetic and resistivity signatures of the intrusive complexes can be combined to enhance geologic features which may be associated with various types of mineral deposits.

CONTRIBUTION OF AEROGEOPHYSICAL SURVEY PROGRAMS TO MINERAL RESOURCE ASSESSMENT, PROSPECTING, BEDROCK MAPPING, AND CRUSTAL STUDIES IN FINLAND

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Introduction: In the Finnish part of the Fennoscandian Shield, late Archean and early Proterozoic rocks are covered by Quaternary deposits that average 4 m in thickness. Only about 3 percent of the bedrock is exposed at the Earth's surface; 20 percent of the rocks cause aeromagnetic anomalies higher than 50 nT. The corresponding average near distance anomaly is 1800 nT. Regional DGRF-65 anomalies vary from -500 to +800 nT.

High-altitude measurements: The first aeromagnetic program (1951-72) covered the whole Finnish continental area plus adjoining parts of the Baltic Sea (400,000 sq. km, 1 million line km). Track separation was 400 m and flight altitude 150 m. Simultaneous electromagnetic measurements were started in 1954 and measurement of total gamma radiation in 1956. The 20 nT contour maps and electromagnetic profile maps were hand drawn. Aeromagnetic maps were tied to absolute total intensity with lines spaced 40 km in 1968-69. The maps were digitized on a 1 x 1 km grid and a computer processed aeromagnetic IGRF-anomaly map was published in 1980 at a scale of 1:2,000,000.

Low-altitude measurements: The high-altitude program was a compromise between areal coverage and resolution. In 1957-1963 the Survey carried out more detailed measurements for prospecting, as did Outokumpu Co. and Rautaruukki Co. in 1955-79 (400,000 line km). The Geological Survey also studied the possibilities of extensive ground profiling as a continuation of the first airborne program, but abandoned this for the original 1949 objective of covering the most prospective parts of the country at an altitude of 40 m with a track separation of 200 m. The new low-altitude program was started in 1972 specifically in the search for massive sulphide and uranium deposits. The data processing was computer based and in 1975 aeromagnetic horizontal gradient measurement was commenced in order to facilitate map drafting. Besides isoanomaly maps, grey tone regional maps are routinely produced. After 10 years of experience with these new maps, it was decided to cover the whole country with them—a task which will take until 2005. Today 65 percent of the measurements are accomplished.

Petrophysical mapping: Measurements of physical properties of rocks as an aid to map interpretation were started in 1953 and systematic measurements of regional sample sets and drill cores have been carried out since 1963. Basic quantities measured are density, susceptibility, and intensity of remanence plus—optionally—conductivity and IP effect. The petrophysical data base was established in 1973 and consists presently of 70,000 records. A petrophysical program covering all of Finland was initiated in 1980. The laboratory was computerized in 1982 and two new labs were built at the regional offices.

Assessment of ore potential and target selection: The original main aim of the high-altitude aerogeophysical program was to find large iron ore deposits. This was reasonable, because the method was appropriate and such deposits were known beyond the State borders. However just 4 of 163 ore indications led to mining activities. The mines were of medium size and when the potential for new unknown large deposits was low, active iron ore prospecting ceased. Seven Ni-Cu ore deposits in basic rocks were however found. Nineteen new mines were opened, of which in 18 cases, geophysical indications had an essential role in the discovery. Information from known economic deposits including aerogeophysical anomaly properties is compiled into data bases and used for estimating general favorability of ore deposits and distribution of specific ore types throughout the whole country. The exploration department of GSF tests targeting in ore prospecting by numerical models based on aerogeophysical low-altitude data, geological information, and geochemical till analysis. Best results so far achieved are in gold prospecting in early Proterozoic intracratonic environments, but studies in other environments are in progress. Outokumpu Co. has obtained positive results in targeting Ni-Cu exploration from low-altitude data.

Bedrock mapping: In the first half of the century the country was mapped geologically at a scale of 1:400,000 essentially without geophysical support. A new program to cover a total of 342 map sheets on a scale of 1:100,000 was initiated in 1946 and aerogeophysical maps were planned to assist in that work. Since then 14 maps have been prepared without aerogeophysical information, 104 by using high-altitude maps, and 31 based on low-altitude data. The quality differences between these groups are clear, and the older maps will be reviewed in connection with different projects.

Crustal studies: High-altitude data contributed to magnetic maps of NORDKALOTT and MIDNORDEN projects plus the compilation of European and EGT aeromagnetic maps. Forthcoming applications are to aeromagnetic maps of the Arctic and of the World. Interpretations along Finnish DSS-profiles show that magnetic crust is thinner (20-40 km) than seismically defined crust (44-62 km). Archean crust is more homogeneously magnetized than Proterozoic, which may be due to the dominantly paramagnetic character of Archean basic rocks. Surface magnetizations are exceptionally high in Central Finnish Lapland, correlating with the high iron content of all rock types there. Compilation of a crustal model based on magnetic and gravity interpretations is under way.

Other issues: Engineering geology applications included planning of the location of the freshwater tunnel from Paijanne to Helsinki (120 km), the two nuclear power plant and corresponding long-term waste disposal sites, plus underground industrial oil and gas storages in the bedrock. The information interpreted from aeromagnetic maps further indirectly supports environmental studies, geomedicine, and planning of the land use, thus influencing the quality of life in Finland. Not all the forthcoming benefits of mapping programs are known yet. It is expected that the positive effects will accumulate and extend tens of years to the future. The costs of the programs will be compensated also in this way, not only by their contributions to mineral finds as was originally anticipated.

A NEW DEVICE FOR LOGGING THE RESISTIVITY OF DRILL CORE AND ITS USE IN RESEARCH ON CARBONACEOUS METASEDIMENTARY ROCKS

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Visual logging of drill core has proven to be a very inaccurate method either for estimating the carbon content of metasedimentary rocks or for defining stratigraphic units in this type of rocks. Resistivity logging is a proven geophysical method for evaluating carbon-rich metasedimentary rocks. For situations where downhole geophysics are not available, a hand-held device, called CoReLog, was developed at the Minnesota Geological Survey for logging the resistivity of drill core. Continuous resistivity logs produced by this device have been very effective for defining the distribution of carbonaceous units and for accurately estimating the carbon content of drill core.

PROGRESS IN THE GEOLOGICAL INTERPRETATION OF AEROMAGNETIC SURVEYS

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Aeromagnetic surveys have been flown systematically since the mid 1940s, primarily to produce geological information. Whole continents are now covered, or almost covered, by aeromagnetic data of a quality sufficient for geological mapping at 1:100,000 to 1:250,000 scale. Currently, major efforts are being made to reduce the thousands of surveys to single master grids, allowing enhancement, imaging, and integrated interpretation.

Strangely, it is only very recently that this cornucopia of data has been applied systematically in the production of geological maps. In the period up to 1980 it was only on foreign aid projects that geological interpretations were published together with the magnetic maps. In the 1980s, we have noticed a tendency for magnetically interpreted contacts, dikes, and faults to find their way gradually onto published maps, though usually with a disclamer as to reliability. The magnetic signatures of rock fabric and chemistry, however, including the effects of metamorphism and hydrothermal alteration, are seldom, if ever, used in mapping.

Even among exploration geophysicists there is a built-in reluctance to draw lines on an overlay and assign a geological identification. This is believed to stem from a fear of being wrong, aggravated by the lack of a developed, academically based literature on the science and technology of qualitative aeromagnetic interpretation.

In this paper the application of systematic magnetic interpretation in exploration and mapping is demonstrated, some recent advances in the technology are presented, and some suggestions are made as to how the geophysical profession should go about improving the science of geological interpretation.

GEOLOGICAL AND GEOPHYSICAL INSIGHTS ON THE STRUCTURE AND EVOLUTION OF THE SUPERIOR PROVINCE

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The Abitibi-Wawa subprovinces of the central Superior Province are classic greenstone-granite terranes hosting important mineral deposits. Recent recognition that the deep parts of the terrane are exposed in oblique cross section in the Kapuskasing uplift has given rise to multidisciplinary LITHOPROBE studies designed to address problems of regional and global significance. Among these are: (1) the magmatic, metamorphic, and structural processes that shaped the Archean crust; (2) the style, mechanism, and timing of the intracratonic deformation that formed the uplift; and (3) the nature and origin of seismic reflections and enhanced electrical conductivity in the deep crust. The obliquely exposed upper 20 km of crust consists of an uppermost level of metavolcanic (~2750-2695 Ma) and metasedimentary rocks metamorphosed at greenschist facies (2-3 kb), cut by high-level plutons; an intermediate level of tonalitic gneiss (~2720-2660 Ma) crystallized at 4-6 kb; and the deepest layer, characterized by interlayered mafic, tonalitic, metasedimentary and anorthositic rocks in the granulite facies (7-9 kb). Upright structural features at high levels are overprinted by subhorizontal ductile extensional fabrics with increasing structural level. The seismic reflection character, based on combined Kapuskasing and Abitibi LITHOPROBE profiles, involves steep structures giving way to gently dipping reflectors within the upper greenstone-granite layers, a weakly reflective zone corresponding to the tonalitic domain, and a variably reflective deep crust. Beneath the exposed level, reflections of variable intensity and continuity correspond to a region with high (7-7.8 km/s) refraction velocities in a crust of probable mafic composition. The style of intracratonic deformation in the upper crust was imaged on several lines crossing the uplift. The Kapuskasing sequence can be traced through gently west-dipping reflections to depths of ~12 km and deeper, through refraction P-wave velocity contours, to ~20 km. Below 20 km, the velocity contours are subhorizontal but the crust beneath the uplift is thicker than the background 40-45 km by about 10 km. A crustal-scale mechanical model for deformation involves brittle uplift by thrusting above a mid-crustal decollement, coupled with deeper ductile flow into a crustal root.

Geological causes of reflections from deep crystalline crust are generally obscure, and much effort, including deep drilling, has been dedicated to resolving this problem in order to provide a firm basis for interpretation of the deep parts of reflection profiles. Detailed work on part of the Kapuskasing uplift, where prominent reflectors extend to within 1 km of the surface, serves as a model for crustal levels normally located at depths of ~25 km. High-resolution Vibroseis- and dynamite-source profiles record a 1.5-km-thick band of reflections that also appear as UTEM electromagnetic conductors and can be modelled as lithological interfaces. Refraction tomography distinguishes major lithological units on the basis of variable Poisson's ratios. The surface geology, consisting of moderately dipping, interlayered mafic and tonalitic gneiss with minor anorthosite, cannot be correlated through the ~1-km vertical gap with the reflectors, but lab-measured P-wave velocities of 6.5-7.5 km/s for the 10-100 m scale layers generate substantial synthetic reflections. A mafic/felsic package accords with general interpretations for lower crustal reflectivity, however; rather than basaltic sills in felsic crust, the Kapuskasing sequence originated through emplacement of tonalitic sills into a mafic host.

GEOPHYSICAL MAPPING OF REGIONAL GEOLOGY AND WATER RESOURCES

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The Minnesota Department of Natural Resources, Division of Waters, Geophysics Group is the main geophysical service organization for the State of Minnesota. Its primary mission is to apply seismic, EM, and electrical resistivity methods to identify and map the ground-water resources of the state. Other missions include the identification and mapping of mineral resources, general-purpose geologic mapping, and investigations of hazardous waste and solid waste sites. The Geophysics Group also is a service organization to be used whenever one of the above geophysical methods is needed by any state agency.

The major accomplishments of the Geophysics Group to date are seismic investigations for the county geologic atlas program, done in conjunction with the Minnesota Geological Survey (MGS); the mapping of water resources, done in conjunction with the U.S. Geological Survey Water Resources Division, and the Minnesota Department of Natural Resources Division of Waters; and hazardous and solid waste site investigations, done with the Minnesota Pollution Control Agency.

The Geophysics Group conducts seismic refraction surveys to assist in mapping the thickness of the glacial overburden, which covers virtually the entire state. Seismic refraction produces information on the thickness of the glacial overburden, the location of buried bedrock valleys, the lithology and elevation of the bedrock subcrop, and the elevation of the water table. Seismic refraction also assists in defining unconfined aquifer boundaries for ground-water modeling. For example, in sand plain aquifers, the method provides information on the depth to the water table and the depth to bedrock.

The seismic reflection technique looks very promising for mapping intraglacial stratigraphy. We are especially interested in mapping confined drift aquifers, which are common in the western part of the state. Previous studies done by our group include off-end seismic surveys and vertical seismic profiles in the Brooten-Belgrade area of Stearns County. These studies showed that confined drift aquifers are visible by the seismic reflection method. Further work is needed to determine the exact correlation between glacial stratigraphy and seismic data. However, the results to date are very encouraging.

Future work, planned for summer 1991, includes a search for confined drift aquifers in the northwest part of the state in Marshall, Polk, Pennington, and Red Lake Counties. The emphasis will be on buried sand and gravel deposits in the Lake Agassiz Plain.

THE USE OF DOWNHOLE GEOPHYSICAL LOGS IN A HYDROLOGIC STUDY OF THE PRAIRIE DU CHIEN-JORDAN AQUIFER

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Downhole geophysical logs were used to study the lithologic features of the Prairie du Chien-Jordan aquifer as part of a ground-water sensitivity investigation at the Minnesota Geological Survey. Natural gamma logs from about 350 wells across southeast Minnesota were studied. Gamma logs provide the best means to distinguished subtle, but hydrologically important lithologic variations in the basal, clastic part of the aquifer in the subsurface.

The gamma signature of a typical section of the Jordan Sandstone and basal Prairie du Chien Group shows low readings for most of the formation punctuated by high readings from units ranging in thickness from 1 to 40 feet thick. Low gamma readings correspond to a quartzose sandstone lithofacies that is mostly fine to coarse grained and friable. High gamma readings correspond to a lithofacies composed of feldspathic sandstone that is mostly very fine grained and moderately to strongly cemented.

These gamma responses allow us to recognize subsurface textural variations in the aquifer that are not apparent in most cuttings samples. The textural variations correspond to substantial variations in permeability and are thus important parameters that influence ground-water migration.

Correlated gamma logs were used to construct fence diagrams that display the 3-D geometry of lithofacies. The fence diagrams provide a lithologic framework for the hydrologic studies in our project. For example, data on ground-water nitrate concentration in the Prairie du Chien-Jordan aquifer are currently being examined to determine if the aquifer lithofacies distinguished on gamma logs influence contamination susceptibility.

MINNESOTA GEOLOGICAL SURVEY DOWNHOLE GEOPHYSICAL LOGGING PROGRAM

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Rock property measurements obtained by downhole logging can be interpreted to yield geologic information pertinent to several kinds of investigation. The most common application is as stratigraphic control in the Paleozoic sedimentary rock sequences, as reported in water well drillers' logs. The correspondence of gamma signature with lithofacies of a major regional aquifer in this sequence is being used to investigate textural variations and hence pollution sensitivity (see Runkel, above).

Downhole data were used in southwestern Minnesota develop a stratigraphic framework for the Cretaceous rocks that are largely not exposed; the gamma signatures were also used to interpret depositional environments for these rocks.

As part of an investigation of radium in ground water, MGS is attempting to correlate radium occurrences with rock characteristics that are recognizable on available logs. Gamma logging is an effective method for determining the degree and thickness of chemical weathering and hence can be used as an exploration tool to locate kaolin resources in the Minnesota River valley and near St. Cloud. Its use for mapping the glacial materials, which are not areally continuous, is limited to parts of the metropolitan area where wells are close to each other.

Most MGS logs were acquired with a Mineral Logging Systems Model 1200 analog logger, which uses natural gamma, single point resistance, spontaneous-potential, and caliper probes. MGS recently acquired a Century Geophysical Compu-Log Portable, a digital system that makes it possible to use the data with log interpretation, subsurface mapping, and other analysis packages. A single probe runs natural gamma, spontaneous-potential, and single point resistance simultaneously. The data are recorded to disk and can be printed in the field by either a 4-inch thermal printer or a dot matrix printer.

The MGS downhole geophysical data base contains logs from approximately 1800 holes, representing 711,425 feet of logged hole. This file increases by approximately 325 holes or 65,000 feet of logged hole per year. Logs are contributed by commercial loggers, the USGS, and explorationists. Gamma logs are the most abundant, but many other kinds of logs are also available.

USE OF SHALLOW GEOPHYSICAL METHODS IN SOLVING GEOLOGICAL PROBLEMS: A STATE PERSPECTIVE

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This paper provides an overview of the types of geophysical surveys that are commonly applied to shallow geological problems. The decades-old use of geophysical techniques in exploration for petroleum and other mineral resources is well established, in contrast to their application to near-surface environmental problems, which dates only from the mid 1980s .

There are two basic reasons to use geophysical methods to address environmental problems. First, geophysical methods can be used to evaluate the extent of existing problems, to predict where pollutants will go in the subsurface, and to guide exploratory drilling programs. The other reason is to help design facilities to prevent environmental problems. Increasingly, geophysical methods are being used before construction to help assure subsurface integrity at critical locations such as refineries, chemical plants, and waste storage/disposal facilities.

Environmental problems associated with underground pollution sources are related to the flow of fluids. If there is not and never will be any fluid flow at a site, then there is not an environmental problem at that site. In most cases the fluid flow involves liquid but sometimes the problem is with movement of a gas or gases, such as those at the infamous Love Canal site near Buffalo, New York. To the extent that geophysical methods can detect fluids directly or determine shallow stratigraphy, geologic structure, and relative permeability, they are useful in site evaluations. Some recent examples of environmental seismic reflection surveys may help put things in perspective.

Shallow seismic reflection techniques were used to image the bedrock-alluvium interface, near a chemical evaporation pond at a refinery in the Texas Panhandle, for optimum placement of water-quality monitor wells. The seismic data showed bedrock valleys as shallow as 4 m and were accurate to within 1 m horizontally and vertically. All monitor-well borings near the evaporation pond penetrated unsaturated alluvial material. On most of the data the wavelet reflected from the bedrock-alluvium interface has a dominant frequency of around 170 Hz. Low-cut filtering at 24 dB/octave below 220 Hz prior to analog-to-digital conversion enhanced the amplitude of the desired bedrock reflection relative to the amplitude of the unwanted ground roll. The final bedrock contour map derived both from drilling and seismic reflection data possesses improved resolution and shows a bedrock valley not interpretable from drill data alone.

Shallow seismic reflection techniques were used successfully to image an intra-alluvial layer as shallow as 4 m and as deep as 30 m in the Texas Panhandle. The major bedrock structure and several associated structural offsets interpreted on the seismic reflection data were confirmed by drilling. Asymmetric grabens were interpreted on two of the seismic lines. The dominant frequency of most of the reflection data is in excess of 150 Hz. The recorded first-arrivals from 3 m out to a source-to-receiver offset at about 23 m were the air-coupled wave indicating that the P-wave velocity in the near-surface materials is less than 335 m/sec. This shallow seismic technique proved quite valuable in determining aquifer geometry, offset relations of sedimentary materials, and bedrock structural relationships underlying the aquifer. The geophysical interpretations were corroborated by well drilling and coring which were sited on the basis of geophysics. The overall interpretation combining the seismic data, geologic data, and hydrologic data suggests the graben provides increased aquifer storage and directs the ascending seepage along bedrock layers to the surface.

CRUSTAL STRUCTURE OF THE ABITIBI GREENSTONE BELT: NEW MODELS FROM GEOLOGICAL AND GEOPHYSICAL DATA

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U-Pb geochronology and regional geological studies have recently led to a model of arc accretion to explain the east-west-trending subprovinces of the southern Superior Province. Concurrently, local structural studies combined with precise U-Pb geochronology have revealed "out of sequence" stratigraphy in greenstone belts which is best explained by thrust faulting, contrary to simple stratigraphic models of greenstone belts. In the context of these developments, regional seismic reflection experiments have provided significant new insights into the structure of the crust beneath greenstone belts. This presentation will review the models for the crustal structure of the Abitibi greenstone belt and is based on recent studies of Green et al. (1990), Jackson et al. (1990), and Jackson and Sutcliffe (1990).

Lithoprobe seismic reflection profiles from the southern Abitibi greenstone belt reveal numerous subhorizontal reflection zones in the upper 15 km of crust. Shallow dipping subparallel reflectors at depths of less than 12 km are interpreted as low-angle faults and are consistent with "out of sequence" stratigraphy profiles. A subhorizontal reflection zone of regional extent at 6 to 12 km depth is interpreted to be the base of supracrustal assemblages in the Abitibi greenstone belt and may be a tectonic contact. Regional, steeply dipping, gold mineralized fault zones, such as the Destor-Porcupine fault, penetrate to depths of at least 15 km. In general, the Abitibi profiles are consistent with the Kapuskasing crustal model, in which greenstone belts are underlain by a middle layer of felsic intrusions and a lower layer of gneiss and intrusions.

The seismic reflection profiles support tectonic models of the Abitibi greenstone belt that involve regional thrusting. Geological, petrochemical, and geochronological data suggest that the southern Abitibi greenstone belt was juvenile oceanic-arc terrane that was thrust over a terrane containing significant evolved crust at 2.70 Ga.

Green, A.G., Milkereit, B., Mayrand, L.J., Ludden, J.N., Hubert, C., Jackson, S.L., Sutcliffe, R.H., West, G.F., Verpaelst, P., and Simard, A., 1990, Deep structure of an Archean greenstone terrane: Nature, v. 344, p. 327-330.

Jackson, S.L., and Sutcliffe, R.H., 1990, Central Superior Province geology: Evidence for an allochthonous ensimatic, southern Abitibi greenstone belt: Canadian Journal of Earth Sciences, v. 27, p. 582-589.

Jackson, S.L., Sutcliffe, R.H., Ludden, J.N., Hubert, C., Green, A.G., Milkereit, B., Mayrand, L., West, G.F., and Verpaelst, P., 1990, Southern Abitibi greenstone belt: Archean crustal structure from seismic-reflection profiles: Geology, v. 18, p. 1086-1090.

GEOSOLUTIONS TO MINING PROBLEMS: BUREAU OF MINES RESEARCH

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The Bureau of Mines is actively engaged in geophysical research to assist the mining industry in the solution of many day-to-day geological problems. This report focuses on recent advances in crosshole seismic; surface wave dispersion; rock-burst monitoring; ground-probing radar; and electromagnetic hydrologic monitoring technology under development by the Bureau for a wide array of applications in the mining industry. Concurrent with these developments are PC-based software developments in waveform processing and geotomography.

Applications addressed by this research include: the detection and location (geosensing) of hidden fractures in mine structures that affect mine stability and contribute to falls of rock; detection and delineation of voids or abandoned mines and shafts; interpretation of geologic structure in advance of mining; rock mass characterization and classification for mine design and stability analyses; rock-burst and bump detection and location; determination of stress concentration, stress relief and stress change associated with mining activities; and fluid detection and monitoring for hydrological and environmental assessment. These developments have generic application to the mining industry and have application as well in other engineering and environmental fields. In contrast to the more conventional geophysical technology in use in the petroleum industry, mining geophysical research emphasizes high-frequency, high-resolution capabilities in order to describe the smaller scale geologic features of most concern to mining operations.

Crosshole Seismics: Because of extensive potential for geosensing in mining applications, the Bureau has developed three crosshole seismic systems. These systems are undergoing evaluation for different applications in mining. Each system has different characteristics for range, resolution and deployment. One is a very high frequency system (20 kHz), using a piezoelectric, cylindrical source transducer and hydrophone receiver unit. The unique source was developed for the Bureau by the International Transducer Corp. The high-frequency system typically is used at close range (1-20 m borehole separation distance) and provides the highest resolution for small-scale geologic features. It is best used for small-scale fracture/flaw detection, blast damage assessment, and investigations of stress conditions adjacent to mine structures. The second crosshole seismic system has a sparker source, operates in a frequency range between 200 and 2000 Hz, and has a propagation distance for compressional waves of about 300 m in most rock. This system has a patented, 10-kv, electrodeless sparker source and low-noise, high-sensitivity bender mode receiver, both developed for the Bureau under a contract to the Southwest Research Institute. The sparker source system is well suited for intermediate-range detection of voids and abandoned mines, geologic faults and seam offsets, larger scale fracture detection, and hydrologic investigations. The third crosshole seismic system uses a commercially available airgun source and a Bureau-developed wall-locking, multiple-receiver unit (patent applied for). It operates in a frequency range centered near 200 Hz with many of the same applications as the other systems, except that it can operate with somewhat reduced resolution over greater range and in poorer quality rock. Theoretical studies of the relationships between range, frequency, resolution, and energy absorption for different rocks also are being conducted for determining the optimum operating frequency for a given geologic target at a particular range. An objective of these studies is the retention of high frequencies in the wave packet for better resolution of small-scale geologic targets. Geotomographic processing is used in conjunction with the crosshole seismic investigations to obtain velocity images of geologic features. This requires surveys having many raypaths at many angles of incidence through the geologic feature of interest.

Field trials of the crosshole seismic systems to data have demonstrated capability for void detection, stratigraphic and seam offset (fault) interpretation, and the delineation of fractured or saturated zones in the rock mass. The crosshole seismic technology is particularly effective for indicating changes in rock properties or environmental conditions with time; for example, as for monitoring fluid flow and the growth of plumes.

Surface Wave Monitor: Development of a surface (Rayleigh) wave monitoring system for assessing the integrity of mine structures is underway with in-mine field trials scheduled for this summer. The conceptual and modeling stages of this research were recently completed. The modeling, using body wave data from coal mine pillars as input, suggests that differences in Rayleigh wave dispersion characteristics between fractured and intact portions of the rock mass permit an assessment to be made of the integrity of the mine structure. The phase and group velocity difference for Rayleigh waves penetrating to different depths in a mine structure appears to present a useful method for differentiating between zones of stress relief (open fractures), stress concentration, and virgin stress regions.

Ground Penetrating Radar (GPR): Results from recent field investigations using conventional GPR systems were highly successful for detecting fractures and joints at shallow depths in a granitic rock mass. GPR reflections of the fracturing were verified by the measurement of fracture traces on the quarry face. This work is conducted in cooperation with the Minnesota Department of Natural Resources and the Cold Spring Granite Co. and has application for the detection of flaws in rock for rock mass quality assessment and the selection of quarry sites.

Microseismic Monitoring: Rock-burst and rock-bump monitoring research continues, following many years of involvement by the Bureau. Bureau involvement in microseismic research began in the late 30s when Obert and Duvall began measuring rock noise in mines in an attempt to predict rock bursts. Current research at the Bureau is conducted mainly at the Denver and Spokane research centers. Recent advances include the development of an automated microseismic monitoring system (AMMS), the 3-D location of microseismic events, and fundamental research on microseismic waveform analyses and focal mechanisms. The research has regional application particularly for deep mines of the western Coeur d'Alene district and the coal mines in the eastern U.S.

Geophysical Fluid Detection: Recent fluid-detection experiments conducted at the San Xavier site in Arizona in cooperation with the University of Arizona and the Sandia National Laboratories used a variety of electromagnetic surface to surface, borehole to surface and borehole to borehole techniques to locate high-conductivity solutions above and within the water table. Methods employed included CSAMT (controlled source audio-frequency magnetotellurics), TEM (time-domain electromagnetics), and FEM (frequency-domain electromagnetics). Although all methods successfully detected the brine solution when before- and after-injection surveys were compared, the borehole methods were more diagnostic of brine location and migration than the surface methods.

Software Developments: The advances in geophysical technology for mining applications have been assisted by the Bureau software developments BOMSPS (Bureau of Mines Signal Processing Software) for waveform processing, and BOMTOM for geotomographic processing. BOMSPS consists of several modules for improving signal quality to assist in the interpretation of seismic and electromagnetic data. BOMTOM (Bureau of Mines TOMography) is a straight raypath tomography program, based on the SIRT simultaneous iterative reconstruction technique. Both programs are PC-based in the IBM-compatible format and available upon request from the Bureau. Just completed and undergoing BETA testing is the program BOMCRTR (Bureau of Mines Curved Raypath Tomography Reconstruction), which will be available shortly.

In summary, the Bureau is conducting a wide variety of geophysical research for regional applications in mining. Much of the research also has application in other fields, particularly in engineering and environmental applications requiring higher resolution for delineating geologic targets.

COMMON OFFSET RADAR PROFILING FOR DETECTION OF FRACTURES IN IGNEOUS ROCK

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As part of an investigation aimed at improving the health and safety and competitiveness of the mining industry, the Bureau of Mines evaluated the application of common offset radar profiling, using a 250-Mhz ground penetrating radar (GPR) system, for the detection of fractures in igneous rock. A series of radar reflection surveys were conducted to detect and delineate the extent of fracturing at various granodiorite and gabbro quarries and outcrops located in Minnesota. The application of radar profiling for detecting joints, sheeting fractures, and faults and depth to water table was demonstrated to be feasible with minimal processing. Radar reflection interpretations were verified by visual inspection of the rock mass and field mapping of local structure. The radar reflection section provides a simple, rapid and cost-effective means for mapping of shallow (less than 10 m) small-scale fractures (greater than 0.25 cm) in igneous rock masses (characteristic velocities between 0.045 to 0.067 m/ns). Depth or distance estimates to fractures are within 10 percent of the actual, with time-shift compensation necessary only when topographic irregularities exceed 30 cm.

INTEGRATED USES OF AIRBORNE GEOPHYSICAL DATA FOR GEOLOGIC MAPPING AND MINERAL EXPLORATION IN AUSTRALIA

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Australia's ancient, arid land surface is deeply weathered, and surficial cover commonly masks the underlying minerals prospective rocks. Cover predominates over the Archean and Proterozoic terrain, is commonly 5-100 metres thick, can contain maghemite, is often conductive, and is generally a considerable impediment to minerals exploration. Not surprisingly, with cover like this, until the accumulation of adequate regional geophysics, most of Australia's mineral discoveries were made in outcrop areas by prospectors, stockmen, and farmers.

However, over the last 20 years the integrated use of geophysics and geology in areas of cover in Australia, particularly with a basis of airborne magnetic data, has led to spectacular discoveries of base metals and other commodities (e.g., Roxby Downs). Geophysics, in a post-gold-exploration boom in the 1980s, is now poised for new successes in a resurgent base-metals exploration boom.

What can we learn from the experience so far? Where should we be headed?

Geophysical Surveys

First pass regional airborne magnetic survey cover of Australia, commenced in 1951, using 1500-3200 metre line spacing and 150 metre ground clearance, is 95% complete, and second pass airborne surveys by government agencies now routinely use 400-500 metre line spacing, and 80-100 metre ground clearance. Survey coverage undertaken by government agencies is estimated to total at least 250,000 line km per year.

Australia has a regional gravity coverage with a 7-11 kilometre grid, and this is constantly being augmented by detailed surveys in minerals and petroleum provinces.

There is presently a boom in the acquisition by mineral exploration companies of large areas of magnetic and gamma spectrometer data at 200-metre line spacing and 40- to 80-metre ground clearance. It is estimated that Australia's three airborne survey contractors are flying a total of at least 750,000 kilometres per year of this kind of survey. Surveys are now routinely processed to image processing quality by use of specialized techniques including "microleveling." The use of active source electromagnetic surveys is increasing.

Integrated Mapping and Exploration Interpretation

Broadly speaking, in the preparation of regional geological maps, government geologists over most of the last 40 years have neither adequately used nor explained the significance of airborne geophysical anomalies. Often, the airborne magnetic and gamma spectrometric survey of a particular 1:250,000-scale map sheet was not flown until after the geological map was produced. To be fair, for 30 of the years, the tools for interpretation were inadequate.

However, both the timing problem and the tools situation have changed. Second pass government geological maps are being prepared, on a basis of airborne geophysics integrated with satellite and other imagery. The use of image processing techniques, including overlaying of satellite imagery, airborne geophysics, gravity and rasterised geologic maps is now becoming commonplace amongst mapping geologists, structural specialists, and orebody modelers.

There is increasing development of interpretation of airborne geophysics by minerals explorers, university researchers, and government surveys. Developments have been made in several areas.

- Magnetic Domain map - textural analysis of large areas of magnetics (commonly at 1:1,000,000 scale),
- Geomag maps - textural analysis of magnetics and gamma spectrometrics combined with mapped lithological information (commonly at 1:50,000 and 1:100,000 scale),
- Structural analysis map - detailed pattern tracing with magnetics and gamma spectrometrics to highlight deformation characteristics (commonly at 1:50,000 and 1:100,000),
- Lineament analysis maps - commonly sub-continental in coverage (scales to suit),
- Mineral exploration target maps (any scale),
- Lithology, geochemistry and rock property databases - some are focussed on specific anomalies, others on regional properties.

The most significant developments have been made with magnetics.

The nature of the developments to some extent reflects the different corporate goals of the groups, and the individual or team approach applied. Greater understanding would have been achieved if the level of funding for drilling had been higher.

What Has Been Found?

Airborne geophysical surveys, particularly combined magnetics and gamma spectrometrics, now routinely are the major tools for penetration of the cover, recognition of windows in the cover, target selection, and direct detection of mineral deposits.

In the last 20 years there have been superb discoveries of blind mineral deposits made as a direct result of integrated use of airborne surveys, other regional geophysics, imagery and geological maps. For example Roxby Downs Cu-Au-U, Elura Cu-Pb-Zn and Scuddles VMS.

Some Problems and Remedies

We have learned from experience in outcrop areas that some of the significant orebodies have no diagnostic airborne magnetic and gamma spectrometric signature. For example Broken Hill Pb-Zn-Ag. This has a bearing on search under cover. Other methods are required.

There is a general lack of relevant factual, detailed geology, mineralogy, geochemistry, and rock physical property data which can be used to explain the causes and significance of geophysical anomalies.

The problem has been created by a general lack of systematic geophysical target identification and follow-up. To some extent this is also related to poor funding of drilling programs and a shortage of susceptibility meters amongst government geologists. Geological surveys have just started to address this problem, for example, South Australia.

We have failed to model the third dimension. Yet modeling is one of the greatest advantages of the cover-penetrating magnetic method.

The regional gravity database for Australia mostly is not compatible with the detail and frequency content of airborne magnetics. This gravity data set has passed its "use-by date" and requires upgrading.

There is an almost total absence, in the public domain, of regional airborne active source electromagnetic data.

Where Should We Be Headed?

We need to know more about the airborne response to rocks and mineralization. This can be found by analysis of outcrop. In the absence of outcrop, drilling is an essential tool.

In the areas of cover we need to know where are the chemically, geologically and geophysically prospective rocks. This can only be found by drilling. Possibly, paleochannel geochemical surveys are the best method for targeting prospective areas.

Developments in the regional application of the electromagnetic method are required. We need to learn more about the conductive characteristics of the overburden.

There is a requirement for developments in understanding the geological significance of integrated data sets.

Through these various means we can expect to find orebodies to increase the national wealth.

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DEEP ELECTROMAGNETIC STUDIES OF PRECAMBRIAN TERRAINS IN THE LAKE SUPERIOR REGION

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The electrical conductivity of the Canadian Shield, northern portion of US Midcontinent Rift, and flanking structures has been investigated with the magnetotelluric (MT) method. Major regions of investigation and brief conclusions follow.

1. Bell Creek Granite, near Marquette, Michigan. A great deal of anisotropy was present in this data set, representing fracturing or faulting, affecting single or only a few MT stations. A statistical approach was required to create an overall model. Each station was modeled as three layers: overburden and/or an upper fractured zone, a thick resistive middle layer, and a bottom half space. The thickness of the middle layer from about 60 stations was fit to a third-order two-dimensional polynomial, yielding a body about 15 km thick, which comprises several hundred square kilometers of the Southern Complex.

2. The Jacobsville Sandstone Basin between L'Anse and Toivola, Michigan. Layering (lithologic units) within the sandstone is revealed by MT and supported by recent analysis of drill core. An anticline and a fault, suggested by gravity data, are supported by the MT data. Portage Lake Lavas or Powder Mill Basalts are found in a subsurface wedge several kilometers thick, which thins toward the southeast.

3. The conductive Animikie Basin and the resistive Duluth Complex in Minnesota. Two transects were carried out. Each was about 40 km long. The northern line extended eastward from Babbitt, the southern line extended eastward from Hoyt Lakes. The contact between the Animikie Basin and the Duluth Complex appears as a contrast in electrical properties. It slopes eastward along the transects and steps down to a depth of about 15 km along the traverse. The configuration of major lithologic units is supported by two-dimensional modeling of gravity data. Faulting is proposed to explain large blocks of contrasting resistivity in the cross section. These faults allow previous geologic maps based on magnetics and exposed surface geology to be refined.

4. A 200-km-long transect of the Midcontinent Rift in northern Wisconsin and Minnesota. Based on data character, there is a clear grouping of sites according to geography; sites west of the rift, on the rift and east of the rift illustrate a fundamental asymmetry of geology about the rift, suggesting a Penokean continental margin which preceded the emplacement of the rift. Stations near sedimentary basins within the rift suggest a previously unknown buried layer of sedimentary rock. The relation of this layer to nearby oil leases will be discussed.

The data for this talk were collected, analyzed and interpreted by graduate students Ted Repasky, Richard Wunderman, Don Adams, and Ahmed Loukili. The work was supported by the Minnesota Geologic Survey, Michigan Technological University, and the U.S. Navy through a subcontract with GTE.

APPENDIX C

PUBLICATIONS FOR WHICH THE LCMR-FUNDED DATA WERE USED

1979-1991

GRADUATE RESEARCH THESES

Van De Voorde, B. W.,1980, A geophysical study of a Precambrian crustal boundary in Minnesota: M.S. thesis, Northern Illinois University, 43 p.

Ferderer, R.J., 1982, Gravity and magnetic modeling of the southern half of the Duluth Complex, Minnesota: M.A. thesis, Indiana University, 99 p.

Pierson W.R., 1984, A geophysical study of the contact between the greenstone-granite terrain and the gneiss terrain in central Minnesota: M.S. thesis, University of Wyoming, 84 p.

Carlson, K.E., 1985, A combined analysis of gravity and magnetic anomalies in east-central Minnesota: M.S. Thesis, University of Minnesota, 138 p.

Ferderer, R.J., 1988, Werner deconvolution and its application to the Penokean Orogen, east-central Minnesota: Ph.D. dissertation, University of Minnesota, 282 p.

Schaap, B.D., 1989, The geology and structure of southwestern Minnesota using gravity and magnetic data: M.S. Thesis, University of Minnesota, 78 p.

PUBLICATIONS

1980

Ervin, C.P., Ikola, R.J., and McGinnis, L.D., 1980, Simple Bouguer gravity map of Minnesota, New Ulm Sheet: Minnesota Geological Survey Miscellaneous Map Series M-43, scale 1:250,000.

Ervin, C.P., 1980, Simple Bouguer gravity map of Minnesota, St. Cloud Sheet: Minnesota Geological Survey Miscellaneous Map Series M-44, scale 1:250,000.

Southwick, D.L. , 1980, Subsurface research and scientific drilling in western Minnesota: Minnesota Geological Survey Information Circular 18, 18 p.

1981

Chandler, V.W., Koski, J.S., Hinze, W.J., and Braile, L.W., 1981, Analysis of multi-source gravity and magnetic anomaly data sets by moving-window application of Poisson's theorem: Geophysics, v. 46, p. 30-39.

Chandler, V.W., 1981, Geologic interpertation [text to accompany Simple Bouguer gravity anomaly map of Minnesota]: Minnesota Geological Survey Map S-12.

1982

Chandler, V.W., Bowman, P.L., Hinze, W.J., and O'Hara, N.W., 1982, Long-wavelength gravity and magnetic anomalies of the Lake Superior region, *in* Wold, R.J., and Hinze, W.J., eds., Geology and Tectonics of the Lake Superior Basin: Geological Society of America Memoir 156, p. 223-237 (invited paper).

Chandler, V.W., 1982, Geologic interpretation [text to accompany Aeromagnetic anomaly map of Minnesota]: Minnesota Geological Survey Map S-11.

Ervin, C.P., Van De Voordre, B.W., and Chandler, V.W., 1982, Simple Bouguer gravity map of Minnesota: St. Paul sheet: Minnesota Geological Survey Map M-48, scale 1:250,000.

Beltrame, R.J., Chandler, V.W., and Gulbranson, B.L., 1982, A geophysical investigation of the Cedar Mountain Complex, Redwood County, Minnesota: Minnesota Geological Survey Report of Investigations 27, 20 p.

1983

Chandler, V.W., 1983, Correlation of magnetic anomalies in east-central Minnesota and northwestern Wisconsin: constraints on magnitude and direction of Keweenawan rifting: Geology, v. 11, p. 174-176.

Chandler, V.W., 1983, Aeromagnetic map of Minnesota—Cook and Lake Counties: Minnesota Geological Survey Aeromagnetic Map Series A-1, 2 pls., 1:250,000.

Chandler, V.W., 1983, Aeromagnetic map of Minnesota—St. Louis County: Minnesota Geological Survey Aeromagnetic Map Series A-2, 2 pls., 1:250,000.

Chandler, V.W., 1983, Aeromagnetic map of Minnesota—Pine and Carlton Counties: Minnesota Geological Survey Aeromagnetic Map Series A-3, 2 pls., 1:250,000.

Chandler, V.W., 1983, Aeromagnetic map of Minnesota—east-central region: Minnesota Geological Survey Aeromagnetic Map Series A-4, 2 pls., 1:250,000.

Southwick, D.L., and Day, W.C., 1983, Geology and petrology of Proterozoic mafic dikes, north-central Minnesota and western Ontario: Canadian Journal of Earth Sciences, v. 20, p. 622-638.

1984

Chandler, V.W., Nordstrand, E., and Anderson, S., 1984, Shaded-relief aeromagnetic anomaly map of northeastern and central Minnesota: Minnesota Geological Survey Miscellaneous Map Series M-53, scale 1:1,000,000.

1985

Chandler, V.W., 1985, Interpretation of Precambrian geology in Minnesota using low-altitude, high-resolution aeromagnetic data, *in* Hinze, W.J., ed., The utility of regional gravity and magnetic anomaly maps: Society of Exploration Geophysicists, p. 375-391.

Chandler, V.W., 1985, Aeromagnetic map of Minnesota—central region: Minnesota Geological Survey Aeromagnetic Map Series A-5, 2 pls., 1:250,000.

Chandler, V.W., Jirsa, M.A., and Ikola, R.J., 1985, Simple Bouguer gravity map of Minnesota, Hibbing sheet: Minnesota Geological Survey Map M-56, scale 1:250,000.

Paterson, N.R., and Reeves, C.V., 1985, Applications of gravity and magnetic surveys: The state of the art in 1985: Geophysics, v. 50, p. 2558-2594.

1986

Halls, H.C., 1986, Paleomagnetism, structure and longitudinal correlation of Middle Precambrian dykes from northwestern Ontario and Minnesota: Canadian Journal of Earth Sciences, v. 23, p.142-157.

Holst, T.B., Mullenmeister, E.F., Chandler, V.W., Green, J.C., and Weiblen, P.W., 1986, Relationship of structural geology of the Duluth Complex to economic mineralization: Minnesota Department of Natural Resources, Division of Minerals Report 241-2, 172 p.

1987

Chandler, V.W., 1987, Aeromagnetic map of Minnesota—west central region: Minnesota Geological Survey Aeromagnetic Map Series A-6, 2 pls., scale 1:250,000.

Chandler, V.W., Mills, S.J., and Ferderer, R.J., 1987, Simple Bouguer gravity map of Minnesota, International Falls Sheet: Minnesota Geological Survey Miscellaneous Map M-62, scale 1:250,000.

Southwick, D.L., and Chandler, V.W., 1987, Mica-bearing olivine pyroxenite of possible lamproite-kimberlite affinity in central Minnesota: Economic Geology, v. 82, p. 212-217.

Southwick, D.L. , and Halls, H.C., 1987, Compositional characteristics of the Kenora-Kabetogama dyke swarm (early Proterozoic), Minnesota and Ontario: Canadian Journal of Earth Sciences, v. 24, p. 2197-2205.

Green, J.C., Bornhorst, T.J., Chandler, V.W., Murey, M.G., Jr., Meyers, P.R., Pesonen, L.J., and Wilband, J.T., 1987, Keweenawan dykes of the Lake Superior region: evidence for evolution of the Middle Proterozoic Midcontinent Rift of North America, *in* Halls, H.C. and Fahrig, W.F., eds., Mafic dyke swarms: Geological Association of Canada Special Paper 34, p. 289-302.

McSwiggen, P.L., 1987, Geology and geophysics of the Denham-Mahtowa area, east-central Minnesota: Minnesota Geological Survey Miscellaneous Map Series M-63, scale 1:48,000.

McSwiggen, P.L., Morey, G.B., and Chandler, V.W., 1987, New model of the Midcontinent rift system in eastern Minnesota and Western Wisconsin: Tectonics, v. 6, p. 677-685.

1988

Chandler, V.W., 1988, Gravity studies in the Little Fork and Cook exploration areas, north-central Minnesota, *in* Martin, D.P., Meyer, G., Lawler, T.L., Chandler, V.W., and Malmquist, K.L., Regional study of buried glacial drift geochemistry over Archean terrane in northern Minnesota: Minnesota Department of Natural Resources, Division of Minerals Report 252, v. 1, p. 39-46.

Chandler, V.W., and Horton, R.J., 1988, Complete Bouguer Gravity Anomaly map of the International Falls 1° by 2°quadrangle, Minnesota and Ontario: U.S. Geological Survey Open-File Report 88-265, scale 1:250,000.

Southwick, D.L., Morey, G.B., and McSwiggen, P.L., 1988, Geologic map (scale 1:250,000) of the Penokean orogen, central and eastern Minnesota, and accompanying text: Minnesota Geological Survey Report of Investigations 37, 25 p., 1 loose pl.

1989

Chandler, V.W., 1989, Aeromagnetic map of Minnesota—northwestern region: Minnesota Geological Survey Aeromagnetic Map Series A-7, 2 pls., 1:250,000.

Chandler, V.W., 1989, Aeromagnetic map of Minnesota—southwestern region: Minnesota Geological Survey Aeromagnetic Map Series A-8, 2 pls., 1:250,000.

Chandler, V.W., 1989, Geophysical lineaments in Minnesota from high-resolution aeromagnetic data: *in* Qureshy M.N., and Hinze, W.J., Regional geophysical lineaments—Their tectonic and economic significance: Geological Society of India Memoir 12, p. 145-154.

Chandler, V.W., McSwiggen, P.L., Morey, G.B., Hinze, W.J., and Anderson, R.R., 1989, Interpretation of seismic reflection, gravity, and magnetic data across Middle Proterozoic Mid-Continent Rift System, northwestern Wisconsin, eastern Minnesota, and central Iowa: American Association of Petroleum Geologists Bulletin, v. 73, p. 261-275.

Chandler, V.W., and Morey, G.B., 1989, Seismic history of Minnesota and its geologic significance: An update: Seismological Research Letters, v. 60, p. 79-86.

Chandler, V.W., and Ferderer, R.J., 1989, Copper nickel mineralization of the Duluth Complex, Minnesota—A gravity and magnetic perspective: Economic Geology, v. 84, p. 1690-1696.

Hinze, W.J., Braile, L.W., and Chandler, V.W., 1989, A geophysical profile of the southern margin of the Midcontinent Rift System in western Lake Superior: Tectonics, v. 9, p. 303-310.

1990

Chandler, V.W., 1990, Geologic interpretation of gravity and magnetic data over the central part of the Duluth Complex, Northeastern Minnesota: Economic Geology, v. 85, p. 819-829.

Chandler, V.W., 1990, Explanation for shaded-relief aeromagnetic map of central Minnesota: *in* Hanna, W.F., Geologic applications of modern aeromagnetic surveys: U.S. Geological Survey Bulletin 1924, p. 48-50.

Jirsa, M.A., and Boerboom, T.J., 1990, Bedrock geologic map of parts of Koochiching, Itasca, and Beltrami Counties, north-central Minnesota: Minnesota Geological Survey Miscellaneous Map M-67, scale 1:250,000.

Jirsa, M.A., 1990, Bedrock geologic map of northeastern Itasca County, Minnesota: Minnesota Geological Survey Miscellaneous Map Series M-68, scale 1:48,000.

Chandler, V.W., Hauck, S.A., Severson, M.J., Heine, J., Reichoff, J.E., and Schaap, B.D., 1990, Investigation of kaolin in eastern Redwood County, Minnesota, using gravity, magnetic and electrical resistivity methods: University of Minnesota, Natural Resources Research Institute Technical Report NRRI/GMIN-TR-89-14, 70 p., 3 pls.

Chandler, V.W., and Southwick, D.L., 1990, Aeromagnetic Minnesota: EOS, v. 71, p. 329, 331, and front cover.

1991

Chandler, V.W., and Malek, K.C., 1991, Moving-window Poisson analysis of gravity and magnetic data from the Penokean orogen, east-central Minnesota: Geophysics, v. 56, p. 123-132.

Tesky, D.J., Thomas, M.D, Gibb, R.A., Dods, S.D., Kucks, R.P., Chandler, V.W., Fadaie, K., and Phillips, J.D., 1991, High resolution aeromagnetic survey of Lake Superior: EOS, v. 72, p. 81, 85-86.

Chandler, V.W., (in press), Geophysical characteristics of the Lake Superior region, *in* The Precambrian of the United States: Geological Society of America, Decade of North America Geology (DNAG) Series (invited paper).

Chandler, V.W., 1991, Aeromagnetic map of Minnesota—southeastern region: Minnesota Geological Survey Aeromagnetic Map Series A-9, 2 pls., 1:250,000 (in press).

Chandler, V.W., (in preparation), Shaded relief aeromagnetic map of Minnesota: Minnesota Geological Survey Aeromagnetic Map Series A-10.

Chandler, V.W., 1991, Geophysical solutions to geologic problems of continental interiors: A Minnesota workshop: Minnesota Geological Survey Information Circular 35 (this volume).

Chandler, V.W., and Schaap, B.D., (in press), Bouguer gravity anomaly map of Minnesota: Minnesota Geological Survey State Map Series S-16, scale 1:500,000.

Chandler, V.W., (in preparation), Aeromagnetic anomaly map of Minnesota: Minnesota Geological Survey State Map Series S-17, scale 1:500,000.

Jirsa, M.A., Boerboom, T.J., Chandler, V.W., and McSwiggen, P.L., Preliminary bedrock geologic map of the Cook to Side Lake area, west-central St. Louis County, Minnesota: Minnesota Geological Survey Open-File Report 91-1, scale 1:48,000.

Southwick, D.L., Jirsa, M.A., and Boerboom, T.J., Geologic drilling and mapping - Cook area, St. Louis and Itasca Counties, Minnesota: Minnesota Geological Survey Open-File Report 91-2, scale 1:100,000 plus text.

Southwick, D.L., Preliminary geologic map of Archean bedrock, Soudan-Bigfork area, northern Minnesota: Minnesota Geological Survey Open-File Report 91-3, scale 1:100,000.

Chandler, V.W., and Miller, J.D. Jr., Description of map sheets for the central Duluth Complex shallow drilling projects: Minnesota Geological Survey Open-File Report 91-4, scale 1:100,000 plus text.

ABSTRACTS AND PRESENTATIONS AT MEETINGS

Bowman, P.L., Hinze, W.J., and Chandler, V.W., 1979, Long-wavelength gravity and magnetic anomalies of the Lake Superior Region [abs.]: Geological Society of America, North-central section, 13th Annual Meeting, Duluth, Minnesota, p. 226.

Walton, M.S., and Chandler, V.W., 1980, Geophysical mapping in Minnesota [abs.]: EOS (American Geophysical Union Transactions), v. 61, no. 5, p. 47.

Chandler, V.W., 1980, Correlation of gravity and magnetic anomalies in east-central Minnesota and northwestern Wisconsin [abs.]: Institute on Lake Superior Geology, 26th Annual Meeting, Eau Claire, Wisconsin, Proceedings, p. 22.

Chandler, V.W., Bowman, P.L., Hinze, W.J., and O'Hara, N.W., 1980, Long-wave length gravity and magnetic anomalies of the Lake Superior region [abs.]: Institute on Lake Superior Geology, 26th Annual Meeting, Eau Claire, Wisconsin, Proceedings, p. 42-43.

Chandler, V.W., and Walton, M.S., 1980, Detailed aeromagnetic mapping program in Minnesota [abs.]: Society of Exploration Geophysicists, 50th International Meeting, Houston, Texas [Abstracts], p. 8-9.

Chandler, V.W., 1981, Detailed aeromagnetic surveying program in Minnesota [abs.]: Minnesota Academy of Science, 49th Annual Meeting, Minneapolis, Abstracts of Papers, p. 11.

Chandler, V.W., 1982, Interpretation of high-resolution aeromagnetic data in northeastern Minnesota [abs.]: *in* Society of Exploration Geophysicists, 52nd Annual International Meeting and Exposition, Dallas, Texas, Technical Program Abstracts and Biographies, p. 288-291.

Chandler, V.W., Beltrame, R.J., and Gulbranson, B.L., 1982, A geophysical study of the Cedar Mountain Complex, southwestern Minnesota [abs.]: EOS (American Geophysical Union Transactions), v. 63, no. 33, p. 614.

Chandler, V.W., Watts, A.B., and Gulbranson, B.L., 1982, Magnetic anomaly studies of the northern Animikie basin: Institute on Lake Superior Geology, 28th Annual Meeting, International Falls, Minnesota, Proceedings, p. 7.

Chandler, V.W., 1983, Interpretation of high resolution aeromagnetic anomaly data in northeastern Minnesota [abs.]: Geophysics, v. 48, p. 451-452.

Chandler, V.W., 1983, Investigation of Precambrian geology in Minnesota through processing of detailed aeromagnetic and gravity data [abs]: American Institute of Mining Engineers, 112th Annual Meeting, Atlanta, Georgia, Proceedings, p. 95.

Ferderer, R.J., Chandler, V.W., and Mead, J., 1983, Gravity and magnetic model studies of the southern Duluth Complex, northeastern Minnesota [abs.]: Institute on Lake Superior Geology, 29th Annual Meeting, Houghton, Michigan, Proceedings, p. 15-16.

Chandler, V.W., 1983, Paleomagnetic and magnetic anomaly studies of the northwestern Duluth Complex, Lake County, Minnesota [abs.]: Institute on Lake Superior Geology, 29th Annual Meeting, Houghton, Michigan, Proceedings, p. 7.

Southwick, D.L., and Chandler, V.W., 1983, Subsurface investigation of the Great Lakes tectonic zone, west-central Minnesota [abs.]: Geological Society of American Abstracts with Programs, v. 15, no. 6, p. 692.

Chandler, V.W., and Ferderer, R.J., 1984, Interpretation of aeromagnetic data over the southern Duluth Complex, northeastern Minnesota [abs.]: EOS (American Geophysical Union Transactions), v. 65, no. 16, p. 199.

Chandler, V.W., and Southwick, D.L., 1985, Regional characteristics of the Kenora-Kabetogama dike swarm, Minnesota and Ontario [abs.]: Mafic dyke swarms—International Conference, University of Toronto, Canada, June 4-7, 1985, Abstracts, p. 29.

Green, J.C., and Chandler, V.W., 1985, Diabase dikes of the Midcontinent Rift in Minnesota: A record of Keweenawan magmatism and tectonic development [abs.]: Geological Society of America Abstracts with Programs, v. 17, no. 7, p. 597.

Green, J.C., and Chandler, V.W., 1985, Keweenawan dikes of Minnesota [abs.]: Institute on Lake Superior Geology, 31st Annual Meeting, Kenora, Ontario, 1985, Technical Sessions and Abstracts, p. 31-32.

Chandler, V.W., 1986, Gravity and magnetic anomalies and the structure of the central Duluth Complex [abs.]: Institute on Lake Superior Geology, 32nd Annual Meeting, Wisconsin Rapids, Wisconsin, Abstracts, p. 17-18.

Chandler, V.W., McSwiggen, P.L., and Morey, G.B., 1986, Reinterpretation of the Midcontinent rift system in Minnesota and Wisconsin using gravity, magnetic, and seismic data [abs.]: Geological Society of America Abstracts with Programs, v. 18, p. 562.

Carlson, K.E., and Chandler, V.W., 1986, A combined analysis of gravity and magnetic anomalies in east-central Minnesota [abs.]: Geological Society of America Abstracts with Programs, v. 18, no. 6, p. 558.

Carlson, K.E., and Chandler, V.W., 1986, A combined analysis of gravity and magnetic anomalies in east-central Minnesota [abs.]: Institute on Lake Superior Geology, 32nd Annual Meeting, Wisconsin Rapids, Wisconsin, 1986, Abstracts, p. 15.

McSwiggen, P.L., Morey, G.B., and Chandler, V.W., 1986, Gravity and magnetic modeling of the Midcontinent rift system in Minnesota and adjoining parts of Wisconsin [abs.]: Institute on Lake Superior Geology, 32nd Annual Meeting, Wisconsin Rapids, Wisconsin, Abstracts, p. 56-57.

Ferderer, R.J., and Chandler, V.W., 1987, The utility of Werner deconvolution as a geomagnetic mapping tool in east-central Minnesota [abs.]: Institute on Lake Superior Geology, 33rd Annual Meeting, Wawa, Ontario, Proceedings and Abstracts, v. 33, pt. 1, p. 25.

Bauer, R.L., Southwick, D.L., and Chandler, V.W., 1987, Correlation of aeromagnetic patterns and regional fold geometries in the western Vermilion Granitic Complex, Minnesota [abs.]: Geological Society of America Abstracts with Programs, v. 19, no. 7, p. 582.

Bergstrom, D.J., and Chandler, V.W., 1987, Preliminary paleomagnetic results from the Sioux Quartzite in southwestern Minnesota [abs.]: Geological Society of America Abstracts with Programs, v. 19, p. 188-189.

McSwiggen, P.L., Morey, G.B., and Chandler, V.W., 1987, New model of the Midcontinent rift in eastern Minnesota and western Wisconsin [abs.]: EOS (American Geophysical Union Transactions), v. 68, p. 781.

Chandler, V.W., and Southwick, D.L., 1987, An aeromagnetic perspective on early Proterozoic tectonism in central Minnesota [abs]: Geological Society of American Abstracts with Programs, v. 19, no. 4, p. 192-193.

Chandler, V.W., and Morey, G.B., 1988, Seismicity and crustal structure in Minnesota [abs.]: Geological Society of America Abstracts with Programs, v. 20, no. 5, p. 339.

Southwick, D.L., and Chandler, V.W., 1988, The Appleton geophysical lineament: A regional feature of the Archean gneiss terrane, S.W. Minnesota [abs.]: Geological Society of America Abstracts with Programs, v. 20, no. 2, p. 129.

Chandler, V.W., 1988, Limitations of the magnetic map of North America—a Minnesota perspective [abs.]: Geological Society of America Abstracts with Programs, v. 20, no. 7, p. A146.

Horton, R.J., Chandler, V.W., Bracken, R.E., and Case, J.E., 1989, Regional geophysical studies for the International Falls and Roseau CUSMAP projects [abs.]: *in* Schindler, K.S., ed., U.S.G.S. Research on Mineral Resources 1988, V.E., McKelvey Forum on Mineral and Energy Resources, 5th Annual, Programs and Abstracts: U.S. Geological Survey Circular 1035, p. 33.

Chandler, V.W., and Schaap, B.D., 1989, New Bouguer gravity anomaly map of Minnesota [abs.]: Institute on Lake Superior Geology, 35th Annual Meeting, Duluth, Minnesota, Proceedings, p. 20.

Tesky, D., Chandler, V., Fadaie, K., Hinze, W., Phillips, J., and Thomas, M., 1989, Preliminary interpretation of a high resolution aeromagnetic survey of Lake Superior [abs.]: EOS (American Geophysical Union Transactions), v. 70, no. 15, p. 273.

Kucks, R.P., Chandler, V., Dods, D., Ervin, C.P., Hood, P., McConnel, K., and Tesky, D., 1989, Potential-field anomaly maps of the Lake Superior region [abs.]: EOS (American Geophysical Union Transactions), v. 70, no. 15, p. 276.

Miller, J.D., and Chandler, V.W., 1989, Syn- and post-magmatic structural elements of the Beaver Bay Complex, northeastern Minnesota [abs.]: EOS (American Geophysical Union Transactions), v. 70, no. 15, p. 278.

Chandler, V.W., and Morey, G.B., 1990, The paleomagnetism of the early Proterozoic Sioux Quartzite, southwestern Minnesota [abs.]: Institute on Lake Superior Geology, 36th Annual Meeting, Thunder Bay, Ontario, p. 14-15.

Jirsa, M.A., Southwick, D.L., and Boerboom, T.J., 1990, The significance of regional-scale left-lateral faulting in development of the Vermilion greenstone belt in Minnesota [extended abs.]: Institute on Lake Superior Geology, 36th Annual Meeting, Thunder Bay, Ontario, Proceedings, v. 36, pt. 1, p. 38-39.

Miller, J.D., Schaap, B.D., and Chandler, V.W., 1990, The Sonju Lake intrusion and associated Keweenawan rocks: Geochemical and geophysical evidence of petrogenetic relationships [abs.]: Institute on Lake Superior Geology, 36th Annual Meeting, Thunder Bay, Ontario, p. 66-68.

Chandler, V.W., 1990, Aeromagnetic interpretation of mafic dyke swarms [abs.]: *in* Mafic dykes and emplacement mechanisms: Geological Society of Australia Abstracts, no. 28, p. 22.

Chandler, V.W., and Southwick, D.L., 1990, Interpretation of two dyke swarms in Minnesota from high-resolution aeromagnetic data [abs.]: *in* Mafic dykes and emplacement mechanisms: Geological Society of Australia Abstracts, no. 28, p 21.

Chandler, V.W., 1991, Aeromagnetic surveying program in Minnesota: Past and future perspectives [abs.]: Institute on Lake Superior Geology, 37th Annual Meeting, Eau Claire, Wisconsin, p. 24.