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SUBSURFACE RESEARCH AND SCIENTIFIC DRILLING IN WESTERN MINNESOTA

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TABLE OF CONTENTS

ILLUSTRATIONS

INTRODUCTION

Minnesota citizens benefit in many ways from geological information on the state. As population and complex technology expand, the rocks and glacial materials of the state are called on more and more to provide ground water, mineral commodities, and fuels, and also to accommodate special engineering structures for the safe storage of petroleum, natural gas, heated water, and a bewildering array of waste products. Sound geologic data are essential for proper exploitation and management of the geologic environment and avoidance of serious decision errors. In another sense the rocks themselves pose interesting academic questions about the origin and development of continental crust in early geologic time, and also about the more recent glacial history of the upper midwest. These questions and their answers contribute to the intellectual richness of our lives, and our thinking about them commonly leads to unexpected practical benefits.

Clearly, it is difficult if not impossible to make informed decisions on resource management or land use in areas where geologic data are poor or lacking. It is equally difficult to make intellectual progress on the fundamental questions of geology. Western Minnesota (west of long. 94° W.) is a case in point. Except in the valley of the Minnesota River, conventional surface study of the rocks is frustrated by a nearly continuous cover of soil and vegetation (fig. 1). Similarly, there are few deep natural exposures of the glacial deposits which overlie the crystalline bedrock throughout this flat area, so that detailed knowledge of the glacial materials is restricted to the topmost few meters. Consequently there is a real need for an integrated program of subsurface geological investigations in western Minnesota, including detailed geophysical studies and test drilling, in order to bring geologic knowledge up to an acceptable level for the demands of the 1980's. Some subsurface work has been done piecemeal over the past several decades under private industry, government, and university sponsorship. The Legislature now recognizes that a substantial input of subsurface geological data is essential for effective resource management and planning in western Minnesota, and has appropriated funds for the Minnesota Geological Survey to begin a program of subsurface studies. The rectangular area of west-central Minnesota outlined on Figure 1 is of particular scientific interest in terms of both bedrock and glacial geology, and will be the site of continuing geological and geophysical investigations during 1980 and 1981.

HISTORY OF GEOPHYSICAL STUDIES TO 1970

The earliest magnetic surveys in western Minnesota were made shortly after the turn of the century by iron-mining companies, who used the dip-needle, a simple instrument something like a vertical compass, to search for buried magnetic iron-formations west of the known Vermilion, Mesabi and Cuyuna deposits. No significant iron deposits were found, although many magnetic anomalies were drilled including some in Becker and Otter Tail Counties. The early dip-needle surveys, as well as other more sophisticated magnetic surveys conducted by mining companies in later years, were neither systematic nor regional in scope. Moreover, the data from most of these surveys were not available to the public until many years after the

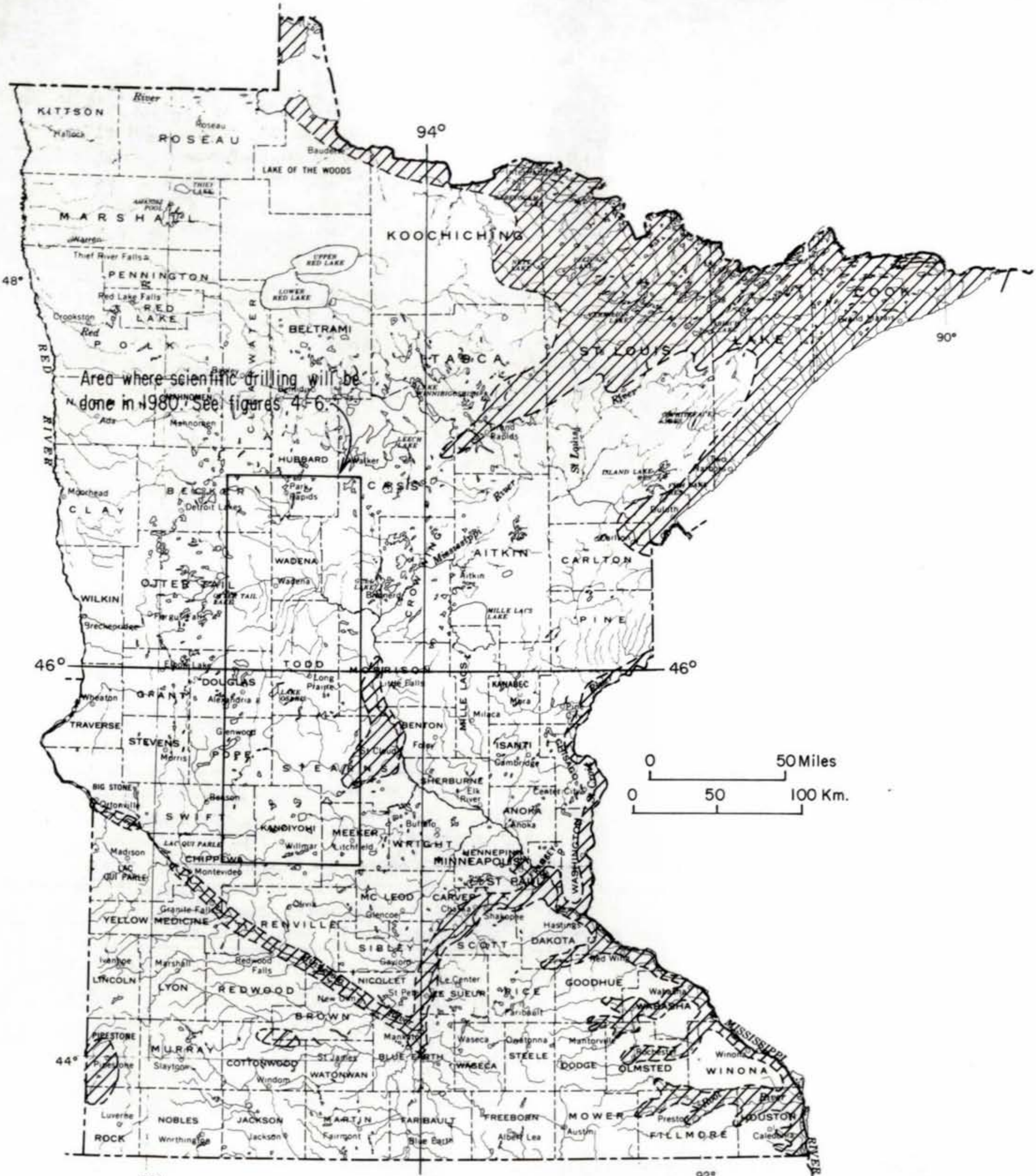


Figure 1 -- Areas of Minnesota (shaded) where natural outcrops of bedrock are adequate for reliable geologic mapping at scale 1:62,500 or larger. Scattered outcrops in the unshaded area provide an inadequate data base for mapping unless augmented by drilling. Note the scarcity of bedrock outcrops west of long. 94° W.

work was done, if then. Consequently the magnetic data accumulated by private industry, though substantial in amount, were inadequate by themselves for assembling a regional picture of the subsurface geology of western Minnesota. In the late 1940's the first government-sponsored aeromagnetic survey in Minnesota was completed by the U.S. Geological Survey (USGS), covering a block of eight counties in the center of the state (see summary in Beltrame, 1978, p. 22-29). This was followed by additional USGS aeromagnetic surveys, largely funded by the state of Minnesota, in the 1950's and 1960's, and by 1970 the entire state had been covered by aeromagnetic maps at scale 1:250,000 or larger. These separate maps were compiled into an aeromagnetic map of the state at scale 1:1,000,000 (Zietz and Kirby, 1970) which proved to be a valuable tool for making regional inferences about the buried bedrock of western Minnesota (Sims, 1970; Morey and Sims, 1976).

Gravity surveying has a history roughly parallel to that of magnetic surveying. The first gravity work was done in the 1940's by mining companies for mineral exploration, and most of it was closely focused on narrow economic targets. Broader coverage gravity maps were made of various parts of the state during the 1960's, chiefly with funds from the Minnesota Geological Survey (see summary in Beltrame, 1978, p. 14-19), and in 1970 a simple Bouguer gravity anomaly map of the entire state was compiled at scale 1:1,000,000 (Craddock and others, 1970). Though the number of gravity measurements was sparse in much of the state, this compilation of the gravity data was nevertheless an important aid to the interpretation of bedrock geology in western Minnesota (Sims, 1970).

Judging from the available public record, neither seismic studies nor electric-field surveys were used systematically in western Minnesota prior to 1970. Apart from a small seismic investigation in Becker and Otter Tail Counties by Beatty (1953), the only published seismic studies were confined to areas east of long. 94° W., and were directed primarily toward understanding the deep structure of the Keweenawan rift (see figs. 2 and 3 and also the summary in Mooney and others, 1970). Electric and electromagnetic exploration techniques have been used extensively since the 1950's in the search for base metal sulfide deposits. Therefore, because base metal exploration has been done by several companies at various times in northwestern Minnesota, electric-field data as old as 10 to 20 years are certain to exist in company files. However the only public electric-field data pertaining to western Minnesota were acquired by the Department of Natural Resources since 1976 (see partial listing in Beltrame, 1978, p. 6-11), and this data base is far too small for meaningful regional interpretation.

GEOPHYSICAL INVESTIGATIONS SINCE 1970

Since 1970 the Minnesota Geological Survey, supported in part by special funds appropriated by the Legislative Commission on Minnesota Resources and the Iron Range Resources and Rehabilitation Board, has undertaken a major effort to improve knowledge of the subsurface geology of western Minnesota. To date, the emphasis has been on acquiring improved geophysical data so that more detailed and more sophisticated inferences can be made about the buried bedrock, and only recently has a program of corroborative test drilling been started.

Simple Bouguer gravity maps at scale 1:250,000 have been completed for all of western Minnesota (McGinnis and others, 1973; 1978a; 1978b; Ervin, 1980; Ervin and others, 1980). These maps are based on gravity observations made on a 1-mile grid throughout the area, a much tighter data spacing than was available for the earlier statewide gravity compilation by Craddock and others (1970). The new maps therefore are a significant refinement.

In the fall of 1979 an ambitious program of high-resolution aeromagnetic surveying was begun that ultimately will provide detailed coverage of Minnesota. Aeromagnetic data are being acquired by a proton magnetometer system mounted in a small single-engine airplane. The survey flight lines are 400 meters (1/4 mile) apart and the flight elevation is 150 meters (500 feet) above the ground. This combination of instrumentation and flight parameters gives a much more detailed picture of the earth's magnetic field than was given by the earlier generation of aeromagnetic surveys, and will greatly enhance geological interpretation of the buried bedrock of western Minnesota. Full coverage of the state will entail several years of flying; most of the work to date has been east of long. 93° W. except for a narrow strip of coverage along long. 95° W., down the center of the rectangle delineated on Figure 1. This strip coincides with the line of the deep seismic reflection profile done by the Consortium for Continental Reflection Profiling (COCORP) in 1979, as discussed more fully below.

The small earthquake of 1975, centered near Chokio, reminded the public that Minnesota is not seismically dead. Minnesota certainly is not seismically active, either, in the sense that California or even the St. Lawrence Valley are, but it does have a record of small, infrequent earthquakes typical of continental interiors. The seismicity of Minnesota has been under investigation throughout the 1970's by the Minnesota Geological Survey with Prof. H.M. Mooney and his students at the University of Minnesota. Aided by funding from the Nuclear Regulatory Commission, they have designed and installed a sensitive seismic listening system in Aitkin, Kanabec, and Isanti Counties to detect very small earthquakes. The several tiny earthquakes detected by the listening array, as well as the Chokio earthquake and most of the other small earthquakes recorded since the 1860's, seem to be related to a system of faults in the bedrock of western Minnesota that is totally obscured from direct observation by the thick covering of glacial drift (Mooney, 1979; Mooney and Morey, in press). Several of the historic earthquake epicenters lie within the Great Lakes tectonic zone of Sims and others (1980), an inferred zone of long-continued geologic activity that trends east-northeast across central Minnesota (fig. 2). This distribution of earthquakes in fact forms part of the evidence for the existence of the tectonic zone, as discussed more fully in the following section.

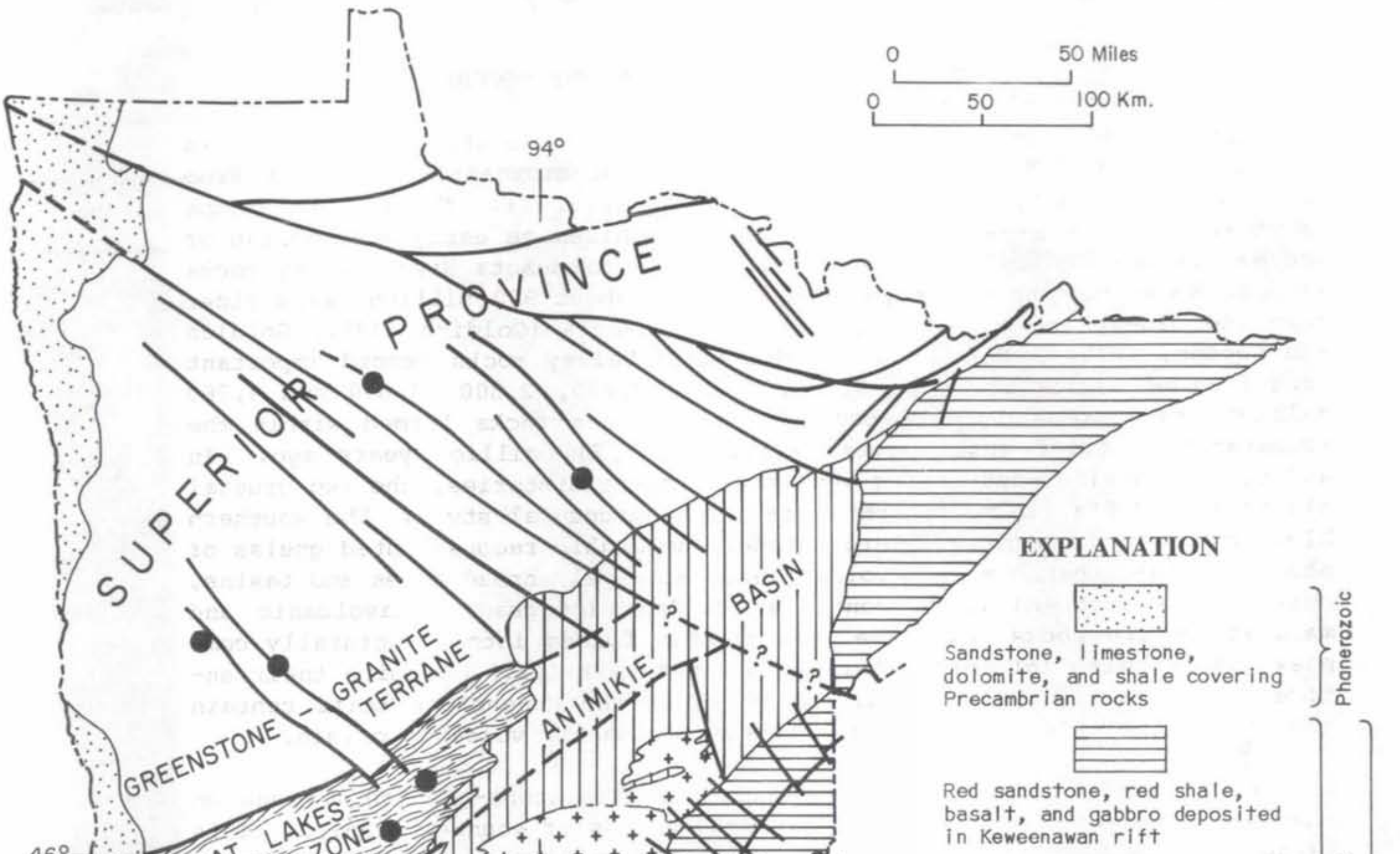


Figure 2 -- Simplified bedrock map of Minnesota showing the major Precambrian terranes and the most prominent faults in Precambrian rocks. Faults dashed where covered by younger strata. Black dots denote epicenters of historic earthquakes. Modified from Morey (1976a) and Mooney and Morey (in press).

THE GREAT LAKES TECTONIC ZONE (GLTZ) AND THE COCORP PROJECT

Careful geologic work spanning several decades has shown that the rocks exposed along the Minnesota River Valley are significantly different from from those exposed north of the Mesabi range (fig. 2). Though both groups of rocks are very old, having long been recognized as early Precambrian or Archean in age (Goldich and others, 1961), the Minnesota River Valley rocks are now known to contain components that are about 900 million years older than the oldest known rocks in northern Minnesota (Goldich, 1972; Goldich and Wooden, 1978). Moreover, the Minnesota Valley rocks record important rock-forming events at about 3,600, 3,300, 3,000, 2,500, 1,850 and 1,760 million years ago, whereas most of the northern rocks formed within the comparatively brief span between 2,650 and 2,750 million years ago. In addition to having contrasting ages and tectonic histories, the two crustal blocks also differ in metamorphic grade and structural style. The southern block consists dominantly of high-grade, thoroughly reconstituted gneiss of obscure origin that has been folded into relatively broad domes and basins, whereas the northern block contains abundant low-grade metavolcanic and metasedimentary rocks that have been tightly folded into structurally complex linear belts informally termed "greenstone belts." Despite their antiquity and strong deformation, the rocks of the greenstone belts contain abundant relict features that prove their dominantly volcanic origin.

The gneiss terrane on the south and the greenstone-granite terrane on the north have both been injected by large masses of younger granite. This large input of granite between 2,500 and 2,700 million years ago apparently welded the two terranes together (Morey and Sims, 1976), but the geologic relationship of the volcanic rocks to the older gneissic rocks prior to the granite emplacement remains conjectural, as do the details of the granite emplacement process.

The contact between the greenstone-granite and gneiss terranes in central Minnesota was first fixed near the southern boundary fault of the presently mapped Great Lakes tectonic zone by Morey and Sims (1976) on the basis of the following combination of indirect geological and geophysical evidence. First, the Animikie basin (fig. 2), which is filled by sedimentary and volcanic rocks that were deposited on the eroded Archean basement about 2,000 million years ago, contains a much thicker, more complex, and more deformed section in the south than it does in the north. The southern deformed part of the Animikie basin was interpreted by Morey and Sims (1976) to have developed over the more mobile gneiss terrane, whereas the northern part developed over more stable rocks of the greenstone-granite terrane. Second, the approximate place where the deformed, thick sequence in the southern part of the Animikie basin gives way to an undeformed, thin sequence coincides with a definite break in the pattern of aeromagnetic and gravity anomalies. This geophysical discordance can be traced beyond the edge of the basin in a southwesterly direction as far as eastern South Dakota (Lidiak, 1971). In general, magnetic and gravity anomalies north of the geophysical break are narrow, steep, and oriented about N. 70° E., corresponding in geometry to the linear form of greenstone belts and to the structural grain of the Superior province of the Canadian Shield (Goodwin, 1974; 1977). Anomalies south of the break, in contrast, are broader, have lower gradients, and are oriented more nearly east-west. Finally, as mentioned above, several of the historic earthquakes in Minnesota have occurred along or close to the magnetic and gravity discordance. This indicates that the boundary zone between the greenstone and gneiss terranes contains fault zones along at least part of its length. Modern motion probably is due to isostatic rebound following glacial unloading of the earth's crust. Vertical adjustments to the added weight and subsequent removal of the Pleistocene ice cap might be expected to occur along pre-existing zones of deep fracturing.

Morey and Sims (1976) suggested that the boundary between the two Archean terranes could be extended eastward across northern Wisconsin and the Upper Peninsula of Michigan. Recent work in Wisconsin, Michigan and Ontario (Sims and others, 1980; Sims and others, in press) has confirmed its extension south of Lake Superior (fig. 3) and as far eastward as the Grenville Front, northeast of Lake Huron. Moreover, it is now clear that the boundary south of Lake Superior is in fact a very complex zone several tens of kilometers wide that has been the locus of repeated deformation, sedimentation, and igneous activity over a long period of Archean and Proterozoic time. Because of its width and geological complexity, the boundary has been renamed the Great Lakes tectonic zone (GLTZ) by Sims and others (1980).

The Great Lakes tectonic zone is completely covered by glacial deposits in western Minnesota and the details of its geology there are poorly known. In view of its width and complexity to the east, however, it is unlikely to be a simple fault or stratigraphic contact, and the most recent interpretations of the new gravity and aeromagnetic data suggest it is a complicated deformed zone on the order of 40 kilometers wide (figs. 2 and 4). The position of the northern boundary is inferred from geophysical anomalies which are nearly as sharply defined as those used by Morey and Sims (1976) to infer the position of the southern boundary. The nature of the rocks between the boundaries is highly uncertain at present, but extensive zones of crushed and sheared Archean gneiss, outlying infolded bodies of Proterozoic strata related to the weakly to moderately metamorphosed sedimentary rocks and volcanic rocks of the Animikie basin, and granite intrusions spanning a wide spectrum of ages are all likely to be present.

Because the Great Lakes tectonic zone is beginning to look more and more like a major continental suture zone, structurally analogous to the boundary between the Churchill and Superior provinces of the Canadian Shield (Bell, 1971), for example, there is increasing academic and economic incentive to learn more about it. The sutures of the Canadian Shield, even where well exposed, are enigmatic features whose ultimate origins are somewhat conjectural (Cranstone and Turek, 1976; Green and others, 1979, 1980). Thus there is considerable scientific interest in documenting the geologic characteristics of the GLTZ, in comparing it with other suture zones of the Canadian Shield, and in striving for a fuller comprehension of this zone and other Precambrian suture zones in general. Furthermore, valuable mineral deposits are associated with the Churchill-Superior boundary in Canada (most notable are the Thompson, Soab, and Chisel Lake base metal occurrences in Manitoba) and thus the possibility exists for similar discoveries along the GLTZ in Minnesota. The probability of making such discoveries cannot be evaluated, however, without detailed geologic knowledge of the zone.

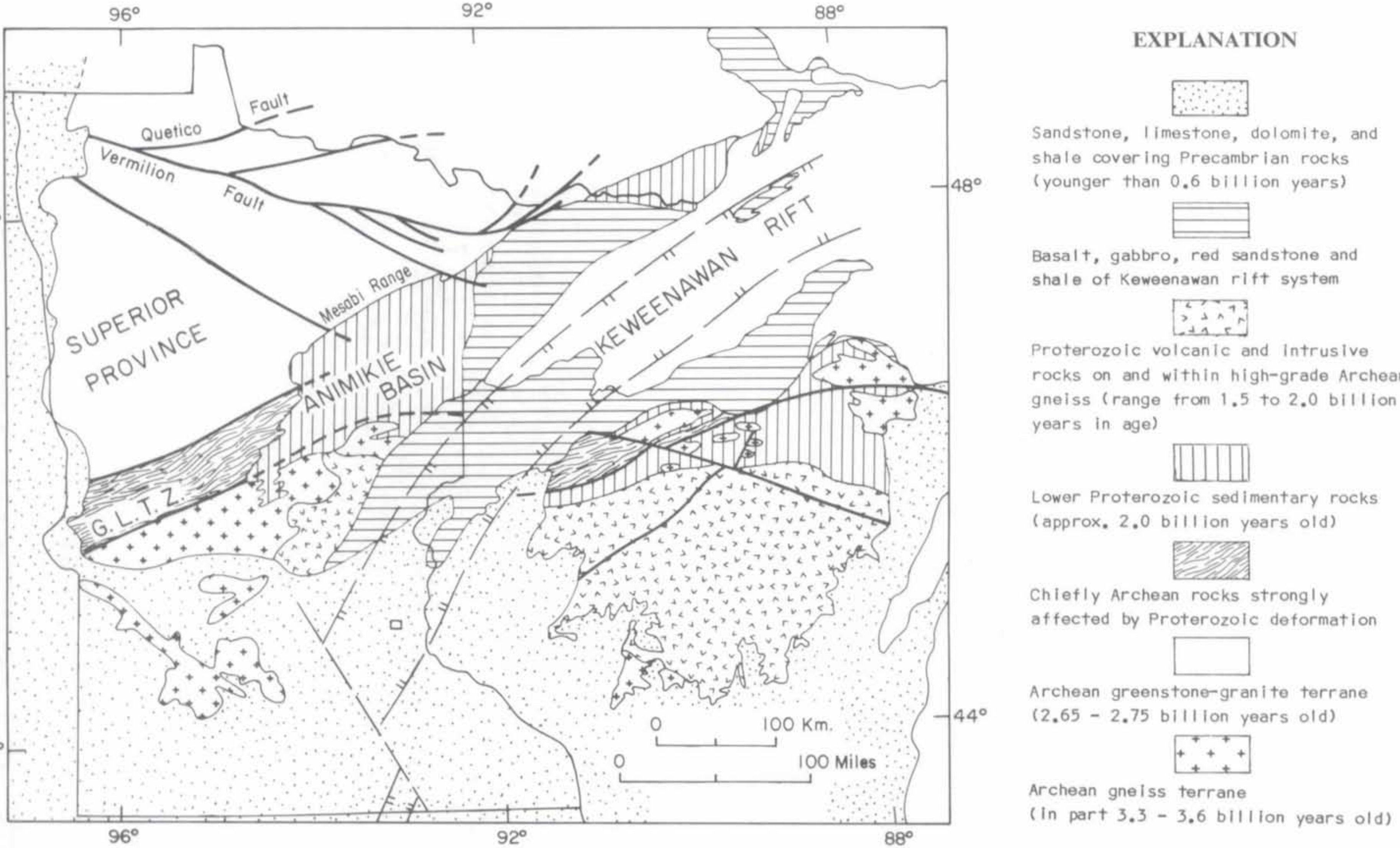
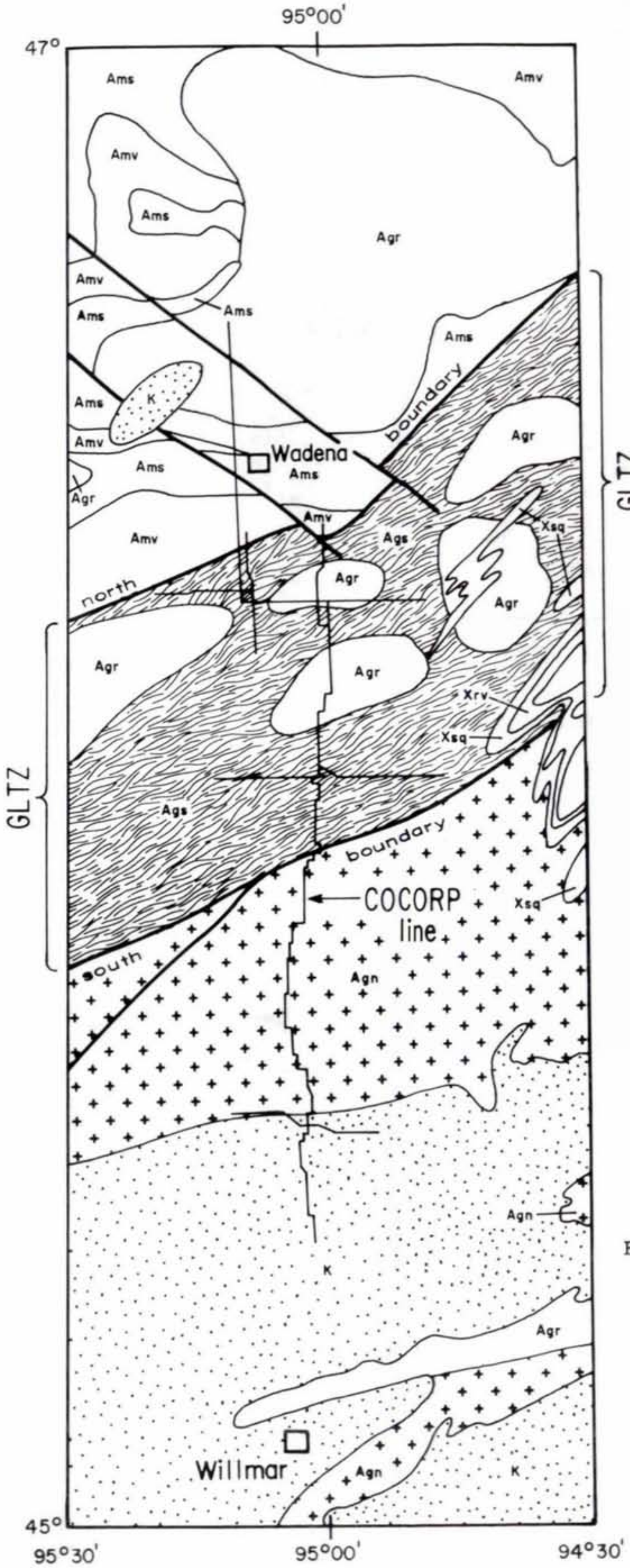


Figure 3 -- Regional tectonic map of Minnesota and adjoining areas showing the Great Lakes tectonic zone (GLTZ) and other major crustal structures. Modified from Sims and others (in press).



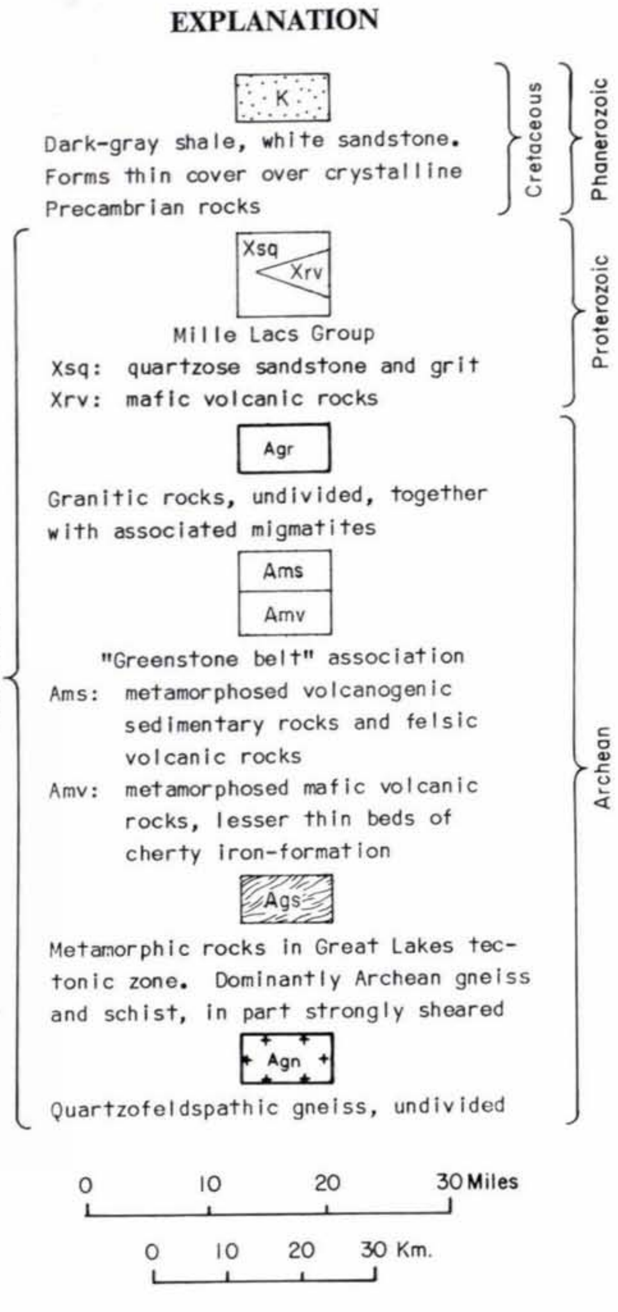


Figure 4 -- Map showing the location of the COCORP seismic survey line and the bedrock geology of the surrounding area. Geology inferred from aeromagnetic and gravity data, water-well data, and sparsely scattered bedrock outcrops. Drilling to be done in 1980 near the COCORP traverse will add important information to this picture.

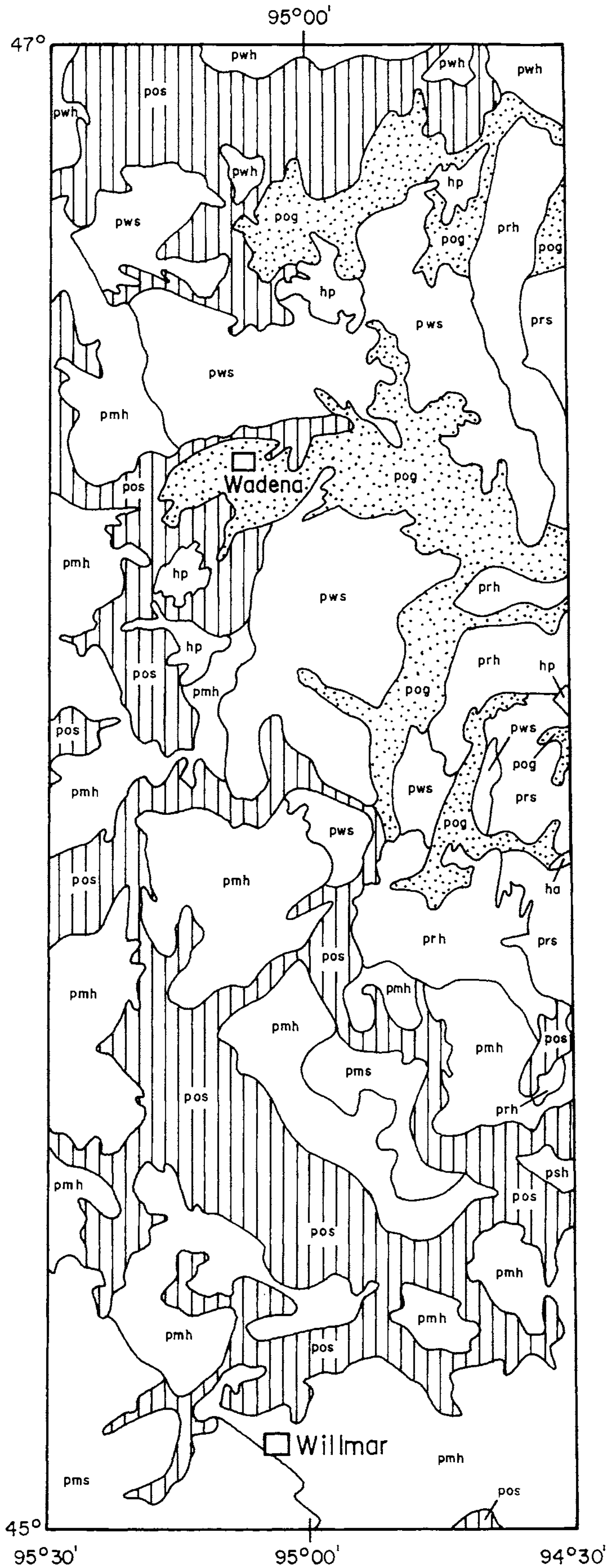
The interest generated from the recognition by Morey and Sims (1976) of a major crustal suture in Minnesota has led to scientific investigations at the national level. In 1979 a deep crustal reflection seismic survey was conducted across the GLTZ in central Minnesota (fig. 4) by the Consortium for Continental Reflection Profiling (COCORP) under the direction of Prof. S. Kaufman of Cornell University. Using heavy-duty truck-mounted vibroseismic equipment developed for oil exploration that is capable of sending a seismic signal to depths of 40 or 50 kilometers, COCORP scientists are attempting to determine the three-dimensional shape of the zone, to find whatever seismic reflectors there may be within the zone, and to test the applicability of the deep seismic reflection technique to the analysis of major crustal structure in an area of complex metamorphic and igneous rocks. The COCORP seismic study is being funded by the National Science Foundation. Results of the survey are still in the data-reduction and interpretation stage but will be made public when analysis is completed.

SCIENTIFIC DRILLING IN WESTERN MINNESOTA

There are two serious deficiencies in fundamental information on the geology of western Minnesota. The paucity of geologic information on buried bedrock has been decried at some length in this report, and improved bedrock data have obvious importance to the search for mineral wealth as well as to geological understanding of the earth's early history. The lack of information on the glacial drift itself is at least as crippling, however, and may be more significant in practical terms. Soil and water resources, our most basic environmental assets, are closely related to geological conditions within the near-surface blanket of glacial deposits.

Although much can be inferred from geophysical parameters about the structure and composition of the buried bedrock, geophysical inferences rarely are unique solutions. The only true test is drilling. Much can be inferred about the topmost few meters of glacial drift from the study of landforms as shown on topographic maps or aerial photographs, and from observations made in natural or artificial exposures at the land surface (fig. 5). The only way to learn about the deeper layers of drift is through drilling, however, because geophysical methods reveal little about glacial deposits except, in some instances, their approximate total thickness (fig. 6). Therefore no scientific program of subsurface investigations in western Minnesota can be complete without test drilling.

Figure 5 -- Map showing the surface distribution of glacial deposits in the vicinity of the COCORP seismic line and the 1980 drilling project. The distribution of these deposits in the vertical dimension and their relationship to older glacial deposits at depth are not known at the present time (see fig. 6). Map modified from Goebel and Walton (1979) and Goebel (in press).



EXPLANATION

HOLOCENE DEPOSITS
(younger than 10,000 yrs)

hp	Peat
ha	Alluvium

PLEISTOCENE DEPOSITS
(10,000 - 20,000 years old)

Late Wisconsinan glacial outwash. Glacial sediment redeposited and sorted by meltwater streams.

pos	Sandy outwash
pog	Gravelly outwash

Late Wisconsinan glacial till. Generally clay-rich, stiff, stony, completely unsorted rock debris deposited directly from glacial ice. Till from different glacial advances (lobes) differs in color, texture and composition.

Till of the Des Moines lobe (m)

pms	forming smooth to undulating landscape
pmh	forming pitted to hilly landscape

Till of the Superior lobe (s)

psh	forming pitted to hilly landscape

Till of the Rainy lobe (r)

prs	forming smooth to undulating landscape
prh	forming pitted to hilly landscape

Till of the Wadena lobe (w)

pws	forming smooth to undulating landscape
pwh	forming pitted to hilly landscape

0 10 20 30 Miles

0 10 20 30 Km.

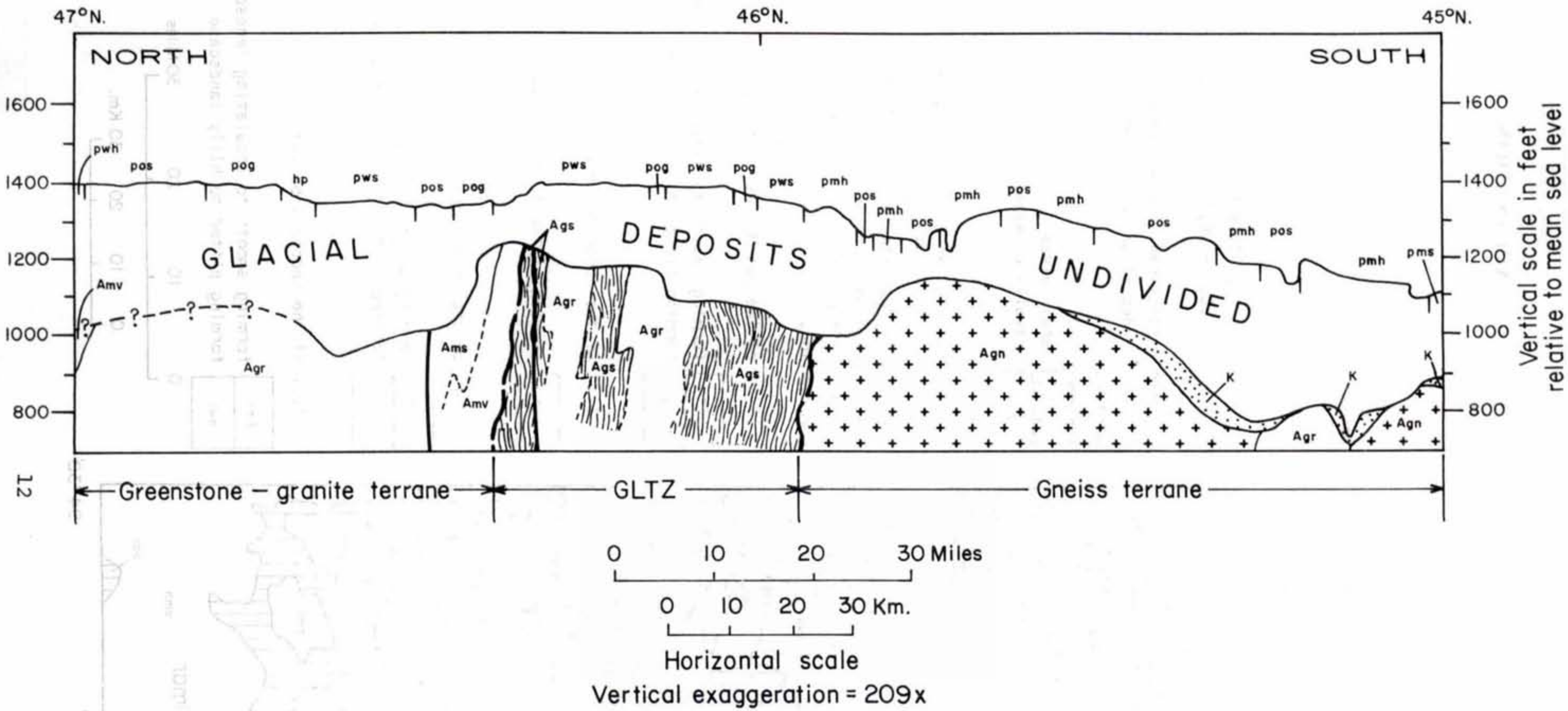


Figure 6 -- Schematic, highly exaggerated geologic cross section along long. 95° W. near the COCORP profile. The bedrock topography and the thickness of the glacial deposits are generalized from very sparse water well data and therefore are subject to large uncertainty. The bedrock geology symbols correspond to those on Figure 4. The symbols for the glacial deposits at the land surface (pmh, pog, etc.) correspond to those on Figure 5.

Until recently virtually no geologic test drilling had been done in Minnesota for broadly scientific purposes. Intensive engineering drilling has been done, of course, for major construction projects in scattered sites throughout the state, and exploration drilling has been done by various mining companies on many mineral prospects in northern Minnesota. In both cases, however, the drill targets have been narrowly defined and the results, with some exceptions, have remained in private hands. For many years the drilling of domestic, commercial, and municipal water wells has provided useful subsurface information, especially on the glacial deposits which are the chief source of exploitable ground water in much of Minnesota. Water-well drilling is a particularly valuable source of geological data when the well cuttings are collected for future study or when the drilling is monitored by a trained geologist. In the usual situation, however, the only record of a given well is a description written by the driller, and this record, though helpful, is not ideal for scientific purposes.

In general, because of its high cost, test drilling has been restricted to situations where the geologic objectives have been closely defined and a reasonable probability has existed for short-term return on investment. Academic institutions and government agencies have been reluctant to engage in drilling for scientific purposes because such drilling has no clear prospects of immediate payoff. In the last 15 years, however, the long-term value of acquiring geological information about the unknown has been recognized increasingly by government science managers, and scientific drilling projects have been funded with public monies through the National Science Foundation, the Office of Naval Research, the U.S. Department of Energy, and other agencies at both federal and state levels. Probably the most successful and most widely publicized government-sponsored drilling project has been DSDP--the Deep Sea Drilling Project--which began in 1968. Information acquired from scientific drilling in the ocean floor has had an enormous impact on ocean science and on earth science in general. It has made major contributions to the verification and refinement of the plate-tectonic model, a major conceptual breakthrough in geologic thought, and it will be useful to both theoretical and applied oceanographic research for decades.

The success of ocean drilling programs together with increasing scientific interest in the long-term geologic development of continents have stimulated planning for a continental drilling program on the scale of DSDP (U.S. Geodynamics Committee, 1979; 1980, p. 33-35). Such a program is likely to involve drilling in the ancient gneiss terrane of southwestern Minnesota, which contains the oldest rocks so far recognized on the North American continent and therefore provides a challenging opportunity to study the early evolution of continental crust. However, the decision as to whether large-scale, deep drilling projects ever come to Minnesota or not depends to some degree on the results from continuing geophysical work and shallow drilling. Much basic work remains to be done on the physical and chemical characteristics of the rocks in the gneiss terrane and the Great Lakes tectonic zone before the wisdom of deep crustal tests can be argued (Morey, 1976b).

SHALLOW SCIENTIFIC DRILLING ALONG THE COCORP LINE IN CENTRAL MINNESOTA

During the summer and fall of 1980, the Minnesota Geological Survey, in cooperation with the Minnesota Department of Natural Resources and the Minnesota Department of Transportation, will undertake a scientific drilling program across the Great Lakes tectonic zone in central Minnesota. The drilling will be done approximately along the line of the 1979 COCORP seismic profile (fig. 4). Forty-three holes will be drilled along public roadways using Department of Transportation drilling equipment and crews. Each hole will penetrate 50 to 150 meters (160 to 500 feet) of glacial drift and will finish in sound crystalline bedrock. Cuttings samples will be taken every 1.5 meters (5 feet) in the glacial drift and split-tube core samples will be taken where warranted by the geologic conditions. Continuous diamond drill cores 1.5 to 6 meters (5 to 20 feet) long will be taken from the bedrock. Laboratory work on the samples recovered will be done at the Minnesota Geological Survey and all results will be published as promptly as practicable.

The scientific aims of this project include better understanding of both the buried Precambrian bedrock and the overlying glacial drift (fig. 6). The primary bedrock target is the Great Lakes tectonic zone. Direct information about the rocks at critical drill sites, when combined with the extensive geophysical data that have been acquired over the zone and its flanking geologic terranes, will vastly enhance our understanding of both the economic and scientific aspects of this enigmatic crustal suture. The bedrock samples will be carefully described and classified, their magnetic and seismic properties will be measured, and some samples may be dated radiometrically. This research, in addition to answering direct questions about the Great Lakes tectonic zone and the bedrock terranes north and south of it, will provide the sort of basic information on the bedrock that is needed for proper planning of more extensive and deeper scientific drilling in the future (Shoemaker, 1975; Morey, 1976b; U.S. Geodynamics Committee, 1979, p. 64-69).

The primary objective of the drilling with respect to the glacial deposits is to establish their stratigraphic succession. Most of the evidence concerning the glacial history of central Minnesota has come from surface studies of the glacial deposits and from careful analysis and interpretation of glacial landforms (Wright, 1972a, 1972b). These investigations and recent studies of LANDSAT images returned from orbiting satellites have established the surface distribution of different glacially-derived materials fairly well (fig. 5), and a complex history of glacial events has been deduced that involves a sequence of advances and retreats of four distinct lobes of glacial ice (fig. 7). However, only fragmentary information

Figure 7 -- Schematic sequence of glacial events responsible for the surficial deposits in the vicinity of the COCORP seismic line and the 1980 drilling project. The heavy rectangle outlines the area of Figure 5. (a) The oldest glacial advance involved the Wadena lobe, which entered central Minnesota from the north and northeast and stopped at the Alexandria moraine. The prominent field of drumlins (streamlined oval hills of glacial origin) south of Wadena was formed during this advance.

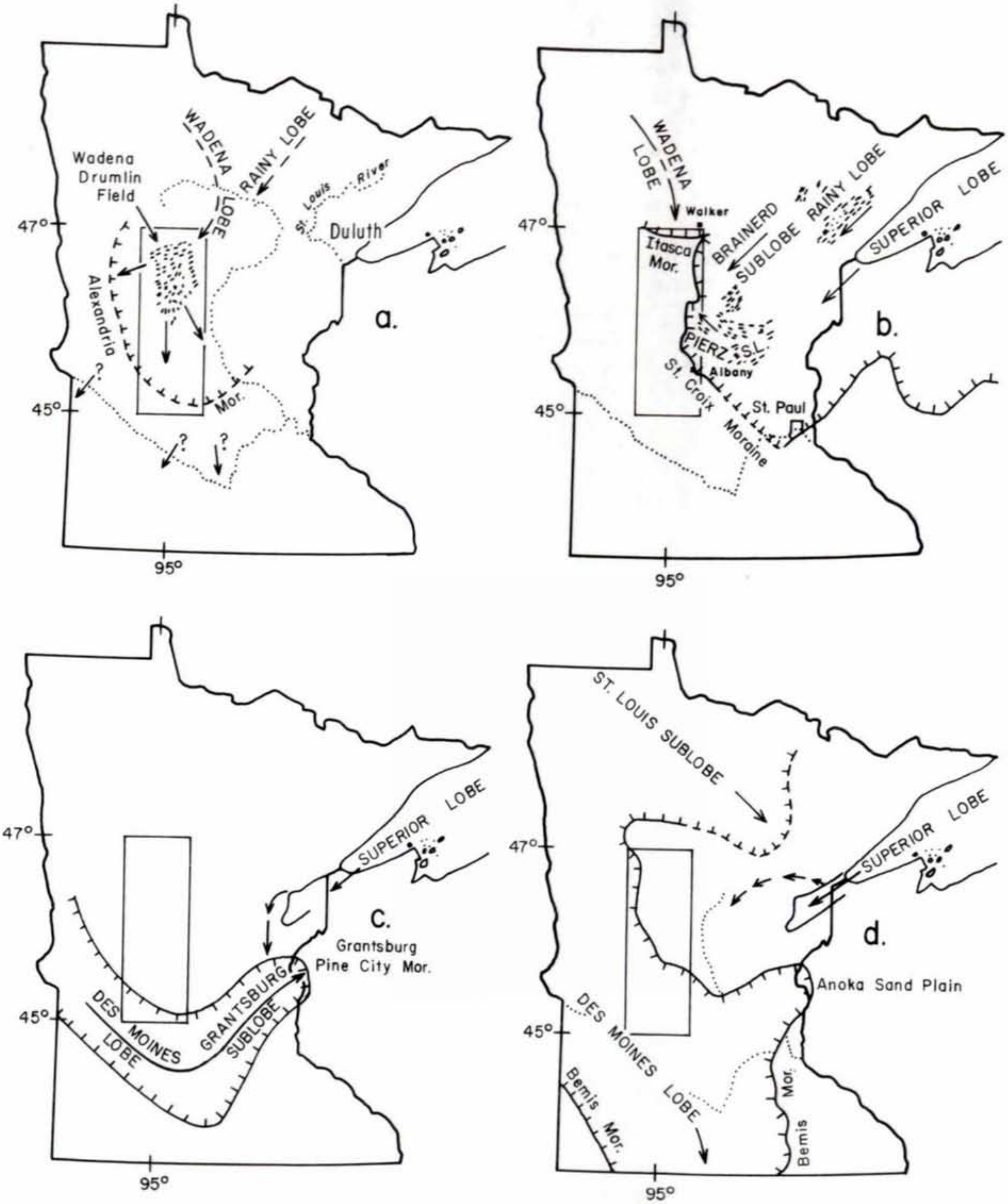


Figure 7 (continued) --

(b) After a period of warming and ice retreat, the Wadena lobe, Brainerd sublobe of the Rainy lobe, and the Pierz sublobe of the Superior lobe readvanced together and stopped at the Itasca and St. Croix moraines. (c) Following a lengthy melt-back, the Des Moines lobe began to advance from the north and northwest, along the Minnesota River lowland. (d) At its maximum stage about 14,000 years ago, the Des Moines lobe occupied about two-thirds of Minnesota. The Des Moines lobe melted from the state about 9,500 years ago, leaving the landscape largely as it is today. Maps modified from Wright, 1972a.

is available on the arrangement of the multiple subsurface layers of till and outwash deposited by the multiple advances and retreats of the Pleistocene glaciers across the area. Subsurface data are so sparse, in fact, that no details of the glacial stratigraphy can be plotted on a geologic cross section along the COCORP survey line (fig. 6). Detailed stratigraphic information obtained from drilling will provide an invaluable geological framework for evaluating the ground-water resources in an area of the state where there is a rapidly growing demand for large-capacity irrigation wells. In addition, it will answer many scientific questions about the complicated glacial history of central Minnesota, including the number of glacial cycles involved, the directions from which the ice advanced in each cycle, and possibly the ages of some of the advances.

The importance of acquiring detailed subsurface geologic information has been emphasized in recent years by the difficulty encountered in trying to make meaningful assessments of the environmental impacts likely to result from public and private projects and developments. An example where decisions are being debated in the absence of sound geological facts is the lingering controversy over the most suitable route or routes (if any) for a new petroleum pipeline across Minnesota. Broad generalizations and "educated guesses" about the subsurface geology are not good enough to meet the increasing demands we are making on our natural environment.

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