MINNESOTA GEOLOGICAL SURVEY

Priscilla C. Grew, *Director*

Information Circular 28

ISSN 0544-3105

GRAPHITE IN EARLY PROTEROZOIC ROCKS OF EAST-CENTRAL MINNESOTA

UNIVERSITY OF MINNESOTA

Saint Paul

1989

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GEOLOGY AND GEOCHEMICAL ATTRIBUTES OF GRAPHITIC ROCKS IN EAST-CENTRAL MINNESOTA

BY

Peter L. McSwiggen and G.B. Morey

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

BY

Peter L. McSwiggen

This project was in part supported by the basic research component of the Minerals Diversification Program as administered by the Minerals Coordinating Committee for the Minnesota State Legislature

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ABSTRACT

The Penokean orogen and southern Animikie basin of east-central Minnesota contain numerous carbonaceous units. The carbon content of these units ranges from as little as 1-2 wt.% to as much as 44 wt.%; the thickness of these units ranges from a few inches to over 500 feet. By using published values for the energy content of some Finnish and Swedish carbonaceous rocks, it is possible to estimate the energy content in samples from this study. These values indicate that a ton of rock with 44 wt.% graphite contains approximately as much energy as one ton of lignite or a half ton of bituminous coal. This suggests that such a rock contains roughly $13.50-19.00/ton worth of energy. In certain localities, the carbonaceous units also contain significant precious and base metal concentrations. Values of as much as 350 ppb gold and 6 ppm silver were recorded.

INTRODUCTION

The Penokean orogen and southern Animikie basin of east-central Minnesota contain numerous carbonaceous units. They may represent a very large source of carbon for the state. Some have been drilled in the course of base and precious metal exploration, but due to their generally barren nature they have been largely ignored. To our knowledge, the only systematic summary of carbonaceous occurrences in the state was compiled by the U.S. Geological Survey as part of its CUSMAP studies in the Archean rocks of the International Falls and Roseau 1:250,000 sheets (Klein and others, 1987). This data base includes carbon analyses as well as trace-metal values for selected grab samples.

Our interest in carbonaceous units in Minnesota was originally stimulated by research on self-reducing taconite processes, such as the MTU–Pelletech Cold Bond Agglomeration Process (Goskel and others, 1985). This process involves combining carbon with the iron in the pellets. Upon heating, the more rapid reduction of iron results in a significant energy savings. The agglomeration process requires about 17% carbon in the taconite pellets.

If such a process were ever to be used in Minnesota, it is clear that a local source for the carbon would be to the economic advantage of the taconite industry. Besides being a reducing agent, the carbon is also a significant source of energy. Therefore, other industries may also be able to utilize this resource in Minnesota.

In addition to the carbon itself as an economic commodity, carbonaceous units are important for other reasons as well. Massive sulfide bodies, which may have their own economic significance for precious and base metals, are commonly associated with them. The origin of the carbonaceous units

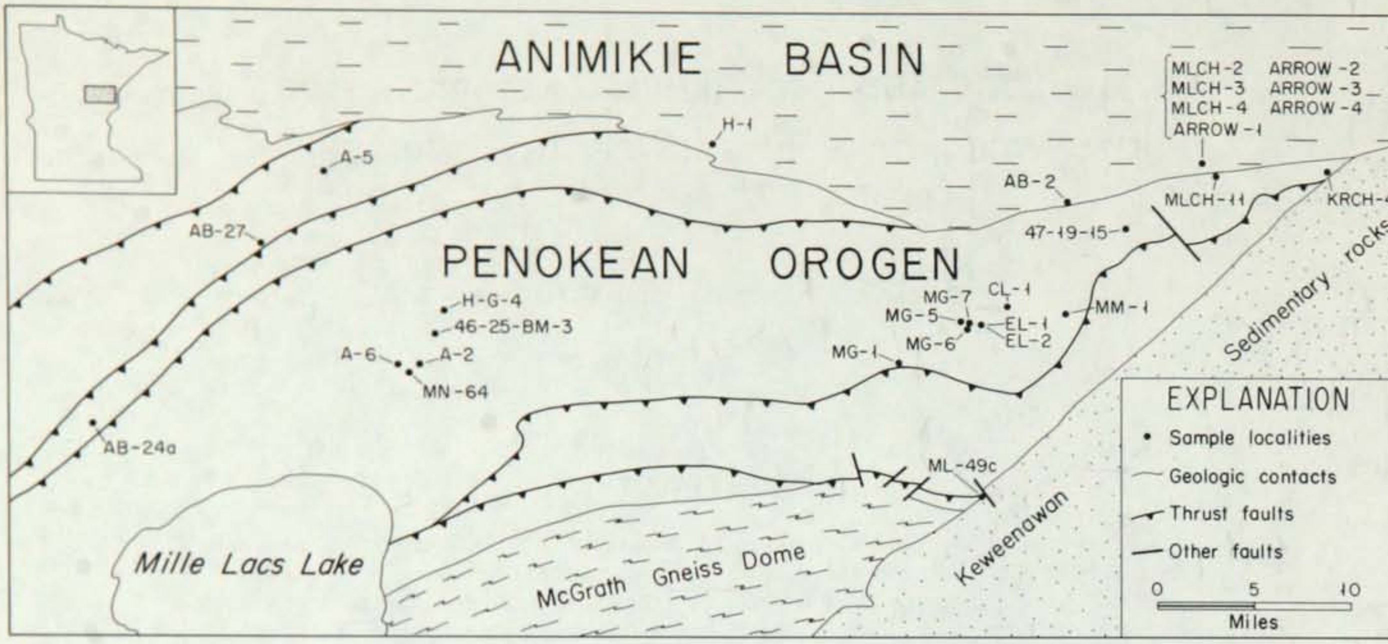

Figure 1. Generalized geologic terranes of the southern Animikie basin and the Penokean orogen with sample and drill-hole locations. Drill hole LV–3 is located 16 miles northwest of the northwestern corner of the map area in the westernmost edge of the Animikie basin.

is also of geologic interest. In some localities these units represent vast thicknesses of originally organic material. One locality contains greater than 500 feet of massive carbonaceous rock with an average carbon content of about 15%. Special circumstances must have been involved to accumulate such a thickness of carbonaceous rocks in old Precambrian terranes.

East-central Minnesota (Fig. 1) was chosen for this investigation because of the abundance of known occurrences of carbonaceous units in the Penokean orogen and Animikie basin. Moreover, electromagnetic surveys, geologic mapping, and bedrock drilling associated with mineral exploration and various research projects have established specific stratigraphic levels where carbon-rich metasedimentary units can be found (McSwiggen, 1987; Southwick and others, 1988). Unfortunately, a thick mantle of Pleistocene material covers much of the bedrock in the area. Consequently, most carbon-rich units can be sampled only by core drilling.

Analytical Procedures

Resistivity logging has been critical in evaluating stratigraphic sequences containing beds and intervals of carbon-rich material in drill core. Characterization of carbonaceous units by visual examination of drill core has proven ineffective, and continuous carbon analysis is prohibitively expensive. Continuous resistivity measurements along the core were very effective in determining the distribution of carbonaceous units and quite accurate in estimating the actual carbon content (McSwiggen, 1989).

A device called CoReLog, developed at the Minnesota Geological Survey as part of this project, was used to make a resistivity log of each core. CoReLog is a hand-held device that feeds the data directly to a micro-computer (McSwiggen, 1989). As the device is moved along the core, the microcomputer monitors the distance traveled and makes resistivity measurements at a predetermined interval. Computer software developed as part of this system allows the user to output the data as continuous strip charts. Thus a geologist logging the core can quickly determine the location and thickness of the carbonaceous units and their approximate carbon content. This in turn makes it easier to determine where samples for chemical analyses should be taken to acquire the maximum information from a minimum number of samples.

A total of approximately 4800 feet of core was logged from 23 drill holes in east-central Minnesota. Varying numbers of samples were taken from each core for analysis. Each sample was coarsely crushed in a jawcrusher and then divided into two equal splits. One split from each sample was sent for whole-rock analyses. The results are listed in Appendix A. The second split from selected samples was finely ground with a ceramic pulverizer. To ensure that the samples would not be overground and thereby damage the crystal structure of the graphitic material, the samples were sieved after each pass through the pulverizer. The sample fraction larger than 105 microns was rerun through the pulverizer, and the fraction between 105 and 63 microns was saved for analysis. This size fraction is fine enough to allow nearly all of the sulfide minerals to be separated, but coarse enough to avoid damage to the crystal structure of the graphite.

The heavy minerals, which in these samples are dominantly sulfide species, were separated using the heavy liquid sodium polytungstate. The principal advantage of sodium polytungstate over traditional heavy liquids such as bromoform and tetrabromoethane is its nontoxic nature. Furthermore it comes as a powder that is mixed with distilled water (Callahan, 1987). Thus it is easily cleaned up and reused. The sample and heavy liquid mixtures were centrifuged until separation was complete. Samples of both the heavy fraction and the light fraction were X-rayed to determine the mineralogy. From selected samples, splits of the heavy sulfide fraction were sent for chemical analyses with the results listed in Appendix B. Splits of the light fraction were immersed in hydrofluoric acid to dissolve the silicate minerals, and the residue of carbonaceous material was then used to determine its crystallinity and isotopic composition.

The degree of crystallinity of the carbonaceous materials is a measure of the change in crystal structure from the material's original amorphous nature to an ordered crystallographic structure as it became a true graphite. This change is gradual and is the result of an increased metamorphic grade. The degree of crystallinity can be measured using the X-ray diffraction technique, in particular from the position and width of the graphite (002) diffraction peak (French, 1968; Landis, 1971; Grew, 1974). This peak occupies the same position as the main quartz peak, and it is for this reason that the silicate minerals must be removed from the sample.

From each carbon sample, four acetone smears were prepared for X-ray. Two were used to measure the position of the (002) peak. This was done by adding a small amount of optically pure fluorite to them as an internal standard. Changes in the position of the (002) graphite peak were then measured against the fixed position of the (111) fluorite peak. The remaining two slides contained no internal standard and were used to measure the width of the (002) peak. Scans were made using copper radiation and a nickel filter at a speed of 0.5° 2θ/minute while the recording paper moved at a rate of 0.5 inch/minute. Each slide was scanned twice, once in each direction. The peak widths were measured at one-half the peak height. Average values were determined from all of the scans, and these values are reported in this study.

DESCRIPTION OF CARBONACEOUS UNITS

The carbonaceous units in east-central Minnesota are extremely variable. They range in thickness from a few inches to more than 500 feet (Appendix C), and in carbon content from as low as 1-2 wt.% to as high as 44 wt.% (Appendix A). The units typically are interbedded with graywacke, slate, chert, mafic volcanic rocks, and all of their metamorphic equivalents. A few localities where phosphorite is associated with carbonaceous units also have been reported (McSwiggen and others, 1986).

The carbonaceous units themselves range from carbonaceous slates to carbonaceous massive sulfides to siliceous carbonites. The term siliceous carbonite is used here informally for rocks that contain more than 40 wt.% carbon, some quartz, and very little if any alumina, such as sample AB–27–210–1 (Appendix A). It is clear that rocks of this kind, which contain less than several weight percent alumina, must contain little if any feldspar, mica, or clay minerals, which are prominent in most clastic sedimentary sequences. The mineral compositions of the siliceous carbonites are predominantly quartz, carbonaceous material, pyrite, and goethite. Whether the origin of the goethite is primary or secondary is not clear at this time. In general the mineralogical and chemical attributes of the carbonite suggest that it was chemically precipitated and thus does not contain a significant clastic component.

Most of the samples analyzed have appreciable alumina values and fall into the category we call carbonaceous mudstone. The silicate minerals in those rocks include quartz, muscovite, and plagioclase. In addition to the silicate minerals and carbonaceous material, the mudstones also contain a variety of sulfide minerals dominated by pyrite and pyrrhotite. However, very minor quantities of sphalerite, chalcopyrite, and galena have been recognized. The mudstones have sulfur contents ranging from less than 1 wt.% to approximately 26 wt.% of the rock (Appendix A). These values are equivalent to less than 1 wt.% pyrite to approximately 50 wt.% pyrite. Samples at the high end of this range would more appropriately be called massive sulfides. The sulfide minerals appear to be chiefly syngenetic in origin, though some are clearly epigenetic as evidenced by their occurrence as void filling around brecciated fragments of the host rocks.

Units that contain less carbon than the siliceous carbonite and less alumina than the mudstones fall into the category of carbonaceous chert. These rock types tend to be thicker bedded, more homogeneous, and contain little evidence of bedding as compared to the carbonaceous mudstones. Histograms of the measured resistivity of a few carbonaceous chert units (Fig. 2) show that the units are very uniform in carbon content.

In texture, all the samples of this study are very fine grained, with the exception of the sulfide minerals. The silicate minerals and carbonaceous material are tightly intergrown on a very fine scale. Work done in Michigan on similar rocks has shown that the actual graphite grains typically are 1 to 5 microns in diameter, but occur in aggregates 5 to 100 microns in diameter (Hwang and others, 1986). These workers have been able to show some success in separating the carbon from the silicate minerals by using flotation and heavy liquid separation techniques on samples ground to finer than 400 mesh (38 microns).

Precious and Base Metals Associated with Carbonaceous Units

Anomalous values of both precious and base metals have been found in the carbonaceous units of the study area. In general, high values for the suite of samples from this study include 6 ppm Ag, 350 ppb Au, 2500 ppm Cu, and 3300 ppm Zn. The highest silver (6 ppm) and copper values (2500 ppm) are from a sample (AB–27–210–1) of homogeneous siliceous carbonite from near the town of Aitkin, Minnesota. These rocks are brecciated and cemented with a stockwork veining of quartz. In addition to the high metal values, this sample also is characterized by the largest carbon content of any sample in this study and also has anomalously high values of As, Cl, Mo, Sb, and Se, but is low in Au and Rb.

The highest gold values (150 to 350 ppb) found in this study are from an area northwest of the town of Mahtowa, Minnesota, near the Arrowhead mine locality (samples: Arrow–1 to 4, and MLCH–2 to 4). Nearly all of the carbonaceous rocks at this locality are considerably brecciated

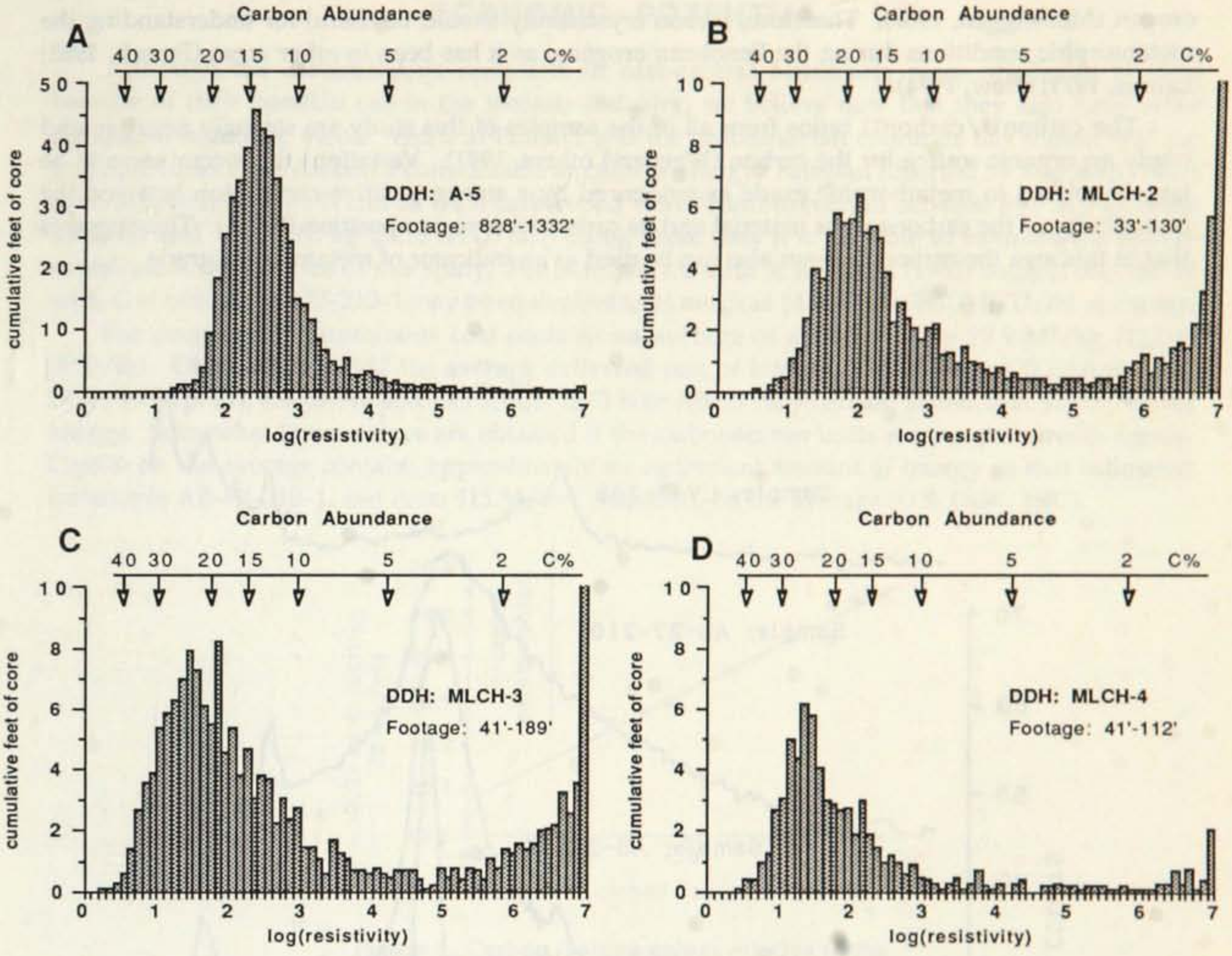

Figure 2. Histograms of the resistivity values measured across carbonaceous units in four drill holes.

and the fragments are cemented with quartz and pyrite. The brecciated fragments are very angular and have numerous slickenside surfaces, but these surfaces seem to have no preferred orientation. Additionally, the pelitic rocks stratigraphically above or below the carbonaceous units are neither brecciated nor are they significantly mineralized by quartz or pyrite. These samples have low Ag and Rb values, but are anomalously high in As, Mo, Sb, and V.

Carbonaceous units and their associated massive sulfide units from elsewhere in the study area typically do not contain appreciable quantities of gold or silver.

Crystallinity and Carbon Isotopes

Preliminary results of this study show that the carbonaceous material ranges from nearly amorphous to almost completely crystalline graphite (Fig. 3; Table 1). The least crystalline sample of this study is from the westernmost edge of the Animikie basin, and the most crystalline samples are from the southern part of the Penokean orogen. These results suggest a metamorphic gradient that increases southward and toward the center of the Penokean orogen. This agrees with the metamorphic gradients as determined from the silicate mineralogy from the eastern part of the orogen (McSwiggen, 1987). Therefore, carbon crystallinity should be useful for understanding the metamorphic conditions during the Penokean orogeny, as it has been in other areas (French, 1968; Landis, 1971; Grew, 1974).

The carbon13/carbon12 ratios from all of the samples of this study are strongly negative and imply an organic source for the carbon (Weis and others, 1981). Variations that occur seem to be largely related to metamorphic grade as evidenced by a strong positive correlation between the crystallinity of the carbonaceous material and its carbon isotope composition (Fig. 4). This suggests that in this area the carbon isotopes also can be used as an indicator of metamorphic grade.

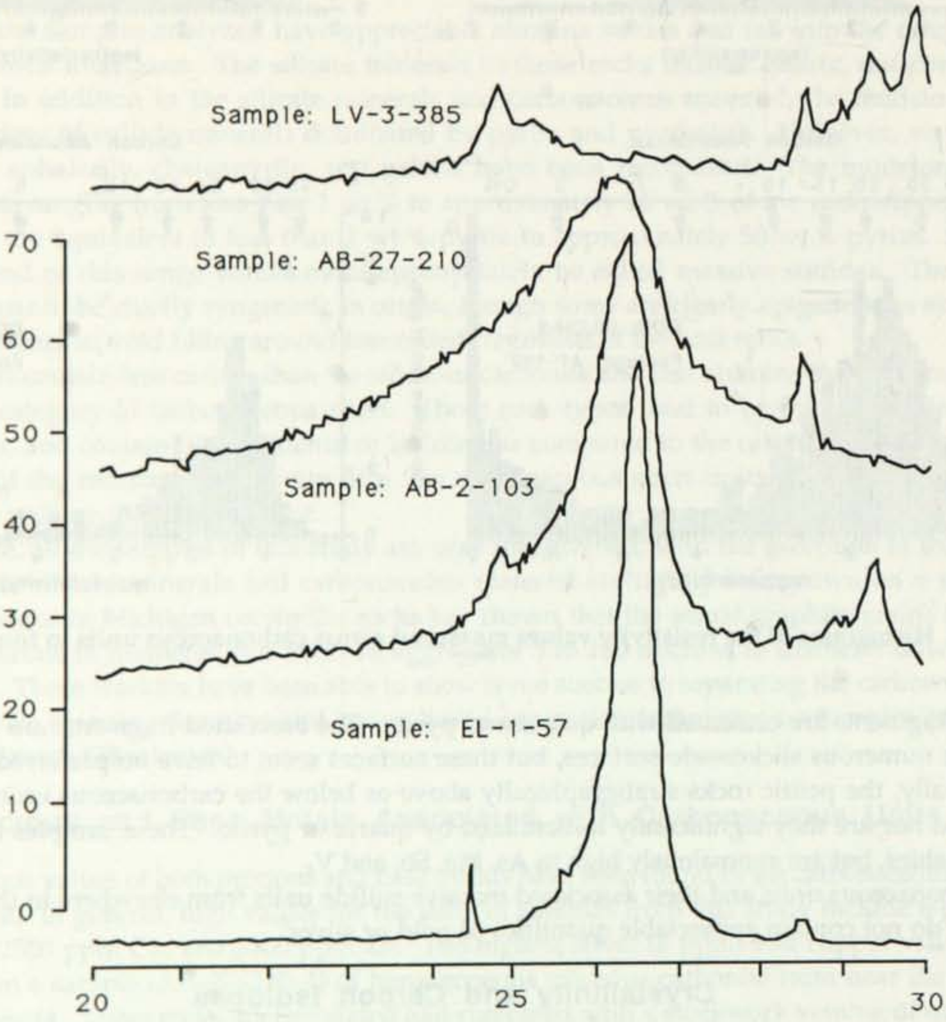

Figure 3. X-ray diffraction patterns of the carbonaceous material at four localities. In sample LV-3-385 there are no peaks related to the mineral graphite. In sample AB-27-210 there is a broad (002) graphite peak, which becomes more sharply defined and moves to a higher 2θ angle with samples AB-2-103 and EL-1-57.

ECONOMIC POTENTIAL

Although the carbonaceous materials in east-central Minnesota were originally studied because of their possible use in the taconite industry, we believe now that they also have other significant economic value. Work in Finland and the Scandinavian countries has shown that the graphitic rocks there contain a considerable amount of energy. Samples reported by Kogonen (1985) contain between 28 wt.% and 38 wt.% carbon and were found to contain between 8.99 MJ/kg (3860 BTU/lb) and 12.15 MJ/kg (5220 BTU/lb). Using these data it is possible to estimate the energy contained in the samples of this study. For example, the data of Kogonen (1985) suggest that the 44 wt.% C of sample AB–27–210–1 may be equivalent to as much as 14.2 MJ/kg (6100 BTU/lb) of energy.

For comparison, bituminous coal contains an average of approximately 27.9 MJ/kg (12,000 BTU/lb). Given that in 1987 the average delivered cost of bituminous coal was $37.88/ton (U.S. DOE, 1987, p. 21), the carbonaceous rocks of drill hole AB–27 may contain as much as $19.00/ton of energy. Somewhat lower values are obtained if the carbonaceous units are compared with lignite. Lignite on the average contains approximately an equivalent amount of energy as that estimated for sample AB–27–210–1, and costs $13.54/ton, delivered, on the average (U.S. DOE, 1987).

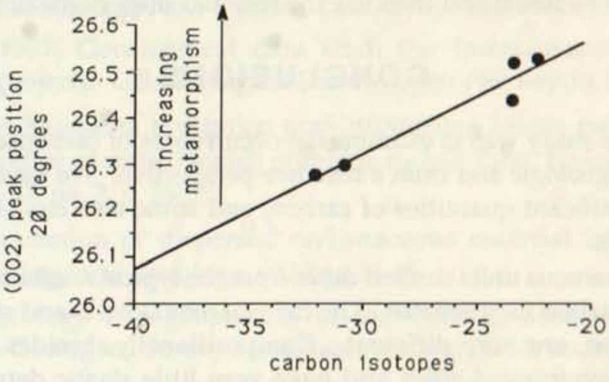

Figure 4. Carbon isotope values relative to the crystallinity of the carbonaceous material. In general, the carbon isotopes become less negative with increasing metamorphic grade as measured by the position of the graphite (002) peak.

Table 1. Peak position & peak width measured at half height of the (002) X-ray diffraction peak of graphite & carbon isotope values

Sample	Peak Position	Peak Width	Carbon Isotopes
LV–3–385	no peak	no peak	-29.20
AB–27–210	26.30°	2.82°	-30.86
Arrow–1	26.28°	1.29°	-32.18
AB–2–103	26.44°	0.95°	-23.59
AB–24a–423	26.52°	0.56°	-23.47
EL–1–57	26.53°	0.49°	-22.44

Any discussion of the real economic value of these rocks must include, however, some additional factors. The sulfur content, for example, would lower the value of these rocks, whereas the silver (AB–27–210–1: approximately $1.00/ton Ag) and gold (Arrow–2: approximately $3.70/ton Au) would increase the value. The high "ash" (all noncombustible material) content would also negatively affect the value of the rock unless a use for it could be found.

For certain industrial processes the "ash," however, also may be a resource. There are a number of industrial processes that require significant amounts of energy and are able to use the quartz that comprises the majority of the remainder of the carbonaceous rocks. For example, cement-making involves burning calcium carbonate ($CaCO_3$) with varying amounts of silica (SiO_2), alumina (Al_2O_3), and/or iron oxide (Fe_2O_3). Temperatures of as much as 1600°C (2900°F) are required, and the cement industry has one of the highest ratios of energy cost to total materials cost of any manufacturing process (Dikeou, 1980). Thus it may be possible to use the carbonaceous rocks both as a source for silica and as a significant contribution to the needed energy.

Silica sand also is commonly used in the making of concrete blocks, and considerable energy is consumed in the curing process when the blocks are held at temperatures of 180°C (350°F) and steam pressures of 8.6 bars (125 psi). It may be possible to use the carbonaceous rocks as a source of energy to generate the high-pressure steam and then use the residual silica in making the concrete blocks.

CONCLUSIONS

The purpose of this study was to examine the occurrences of carbonaceous units in east-central Minnesota both from a geologic and from a resource perspective. We have established that some of these units contain significant quantities of carbon, and some also contain significant amounts of precious and base metals.

Many of the carbonaceous units studied differ from the typical mudstone sequences of the region only in the amount of carbon they contain. The carbonaceous cherts and siliceous carbonites, which contain the most carbon, are very different. Compositionally, besides the carbon, they consist mostly of chemically precipitated silica and have very little clastic detritus. Additionally, they tend to occur as thick and homogeneous entities.

The carbonaceous material ranges from lacking a crystal structure to having a nearly perfect graphite structure. In general, crystallinity increases from north to south in response to degree of metamorphism. Rocks of higher metamorphic grade have more crystalline graphite, which may be easier to separate from the waste material.

We also have shown that it may not be necessary to separate the carbonaceous material from the host rock in order to use it. Other work suggests that a rock containing 44 wt.% graphite, such as sample AB–27–210–1, may contain as much as 14.2 MJ/kg (6100 BTU/lb) of energy. Therefore a ton of this rock would contain the approximate equivalent energy as a ton of lignite or half a ton of bituminous coal. The high noncombustible component of this rock probably would make it undesirable to many coal consumers, but certain industries may find it beneficial.

ACKNOWLEDGMENTS

The project was in part supported by the basic research component of the Minerals Diversification Program as administered by the Minerals Coordinating Committee for the Minnesota State Legislature.

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APPENDIX A

WHOLE-ROCK CHEMICAL ANALYSES

(Blank cells, not analyzed for. The rock unit names under the heading FORMATION are from Southwick, Morey, and McSwiggen [1988]. Depth measured in feet.)

Whole-rock Chemical Analyses

SAMPLE ID	SAMPLE TYPE	COUNTY	QUADRANGLE	TOWNSHIP	RANGE	SECTION	QUARTERS	DEPTH
47-19-15	outcrop	Carlton	Barnum	47	19	15	CBABC	0
AB-2-103-1	core	Carlton	Cromwell SE	47	19	7	CBBCAC	103
AB-24A-423	core	Crow Wing	Bay Lake	45	28	2	CDBCCC	423
AB-27-210-1	core	Aitkin	Aitkin	47	26	19	DDDDDC	210
Arrow-1	outcrop	Carlton	Barnum	48	18	32	BCBCC	0
EL-1-22	core	Carlton	Kettle River	46	20	8	D	22
EL-1-57	core	Carlton	Kettle River	46	20	8	D	57
EL-1-74	core	Carlton	Kettle River	46	20	8	D	74
EL-1-121	core	Carlton	Kettle River	46	20	8	D	121
EL-1-188	core	Carlton	Kettle River	46	20	8	D	188
LV-3-385	core	Cass	Longville	139	28	2	ABABAA	385
Arrow-2	outcrop	Carlton	Barnum	48	18	32	BCBCC	0
Arrow-3	outcrop	Carlton	Barnum	48	18	32	BCBCC	0
Arrow-4	outcrop	Carlton	Barnum	48	18	32	BCBCC	0
CL-1-75	core	Carlton	Moose Lake	46	20	3	CCABD	75
CL-1-104	core	Carlton	Moose Lake	46	20	3	CCABD	104
CL-1-171	core	Carlton	Moose Lake	46	20	3	CCABD	171
CL-1-232	core	Carlton	Moose Lake	46	20	3	CCABD	232
CL-1-259	core	Carlton	Moose Lake	46	20	3	CCABD	259
MG-6-172	core	Carlton	Kettle River	46	20	17	BBABB	172
MG-6-201	core	Carlton	Kettle River	46	20	17	BBABB	201
MG-1-204	core	Carlton	Kettle River	46	21	22	CDDBB	204
MLCH-11-17	core	Carlton	Barnum	47	18	4	BACAC	17
MLCH-11-27	core	Carlton	Barnum	47	18	4	BACAC	27
MG-7-25	core	Carlton	Kettle River	46	20	8	CCABD	25
MG-7-68	core	Carlton	Kettle River	46	20	8	CCABD	68
MG-7-461	core	Carlton	Kettle River	46	20	8	CCABD	461
MG-7-521	core	Carlton	Kettle River	46	20	8	CCABD	521
MG-5-92	core	Carlton	Kettle River	46	20	7	DCABD	92
MG-5-110	core	Carlton	Kettle River	46	20	7	DCABD	110
MG-5-138	core	Carlton	Kettle River	46	20	7	DCABD	138
MG-5-237	core	Carlton	Kettle River	46	20	7	DCABD	237

Whole-rock Chemical Analyses continued

SAMPLE ID	SAMPLE TYPE	COUNTY	QUADRANGLE	TOWNSHIP	RANGE	SECTION	QUARTERS	DEPTH
MG-5-269	core	Carlton	Kettle River	46	20	7	DCABD	269
MG-5-281	core	Carlton	Kettle River	46	20	7	DCABD	281
MG-5-317	core	Carlton	Kettle River	46	20	7	DCABD	317
MG-5-359	core	Carlton	Kettle River	46	20	7	DCABD	359
MLCH-4-68	core	Carlton	Barnum	48	18	33	BCB	68
MLCH-4-80	core	Carlton	Barnum	48	18	33	BCB	80
MLCH-3-89	core	Carlton	Barnum	48	18	33	BDD	89
MLCH-2-103	core	Carlton	Barnum	48	18	33	BDD	103
A-2-631	core	Aitkin	Thor	46	25	21	DD	631
A-2-790	core	Aitkin	Thor	46	25	21	DD	790
A-2-917	core	Aitkin	Thor	46	25	21	DD	917
A-2-981	core	Aitkin	Thor	46	25	21	DD	981
A-5-830	core	Aitkin	Hassman	47	26	2	BB	830
A-5-1010	core	Aitkin	Hassman	47	26	2	BB	1010
A-5-1169	core	Aitkin	Hassman	47	26	2	BB	1169
A-5-1301	core	Aitkin	Hassman	47	26	2	BB	1301
A-6-747	core	Aitkin	Glen	46	25	20	DD	747
A-6-915	core	Aitkin	Glen	46	25	20	DD	915
A-6-976	core	Aitkin	Glen	46	25	20	DD	976
A-6-1120	core	Aitkin	Glen	46	25	20	DD	1120
46-25-BM-3-111	core	Aitkin	Thor	46	25	15	AC	111
46-25-BM-3-133	core	Aitkin	Thor	46	25	15	AC	133
KRCH-4-512	core	Carlton	Atkinson	48	17	32	DD	512
H-G-4-78	core	Aitkin	Thor	46	25	11	BB	78
H-G-4-94	core	Aitkin	Thor	46	25	11	BB	94
H-1-334	core	Aitkin	Lawler	48	22	30	CA	334
46-25-MN-64-94	core	Aitkin	Glen	46	25	28	BD	94
46-25-MN-64-148	core	Aitkin	Glen	46	25	28	BD	148
46-25-MN-64-185	core	Aitkin	Glen	46	25	28	BD	185
ML-49c-378	core	Pine	Denham	45	20	29	AAA	378

Whole-rock Chemical Analyses continued

SAMPLE ID	UNIT LITHOLOGY	FORMATION	AGE	SiO2%	TiO2%	Al2O3%	Fe2O3 total%
47-19-15	graphitic slate	Unnamed Pgvi	E. Prot.	65.60	0.51	13.60	
AB-2-103-1	graphitic slate	Thomson Fm. Pvt	E. Prot.	56.90	0.99	20.20	
AB-24A-423	graphitic slate	Unnamed Pgs	E. Prot.	52.20	1.00	21.50	
AB-27-210-1	siliceous carbonite	Unnamed Pgs	E. Prot.	33.40	0.48	0.62	
Arrow-1	graphitic chert	Thomson Fm. Pvt	E. Prot.	37.30	0.34	5.26	
EL-1-22	graphtic phyllite	Unnamed Pgvi	E. Prot.	57.60	0.74	17.90	
EL-1-57	graphtic phyllite	Unnamed Pgvi	E. Prot.	48.80	0.68	15.90	
EL-1-74	graphtic phyllite	Unnamed Pgvi	E. Prot.	52.80	0.84	23.70	
EL-1-121	graphtic phyllite	Unnamed Pgvi	E. Prot.	45.30	0.94	26.70	
EL-1-188	graphtic phyllite	Unnamed Pgvi	E. Prot.	53.80	0.74	17.30	
LV-3-385	graphitic slate	Virginia Pvt	E. Prot.	61.60	0.80	16.20	
Arrow-2	graphitic chert	Thomson Fm. Pvt	E. Prot.	28.40	0.38	6.20	
Arrow-3	graphitic chert	Thomson Fm. Pvt	E. Prot.	26.40	0.39	6.19	
Arrow-4	graphitic chert	Thomson Fm. Pvt	E. Prot.	27.70	0.45	6.90	
CL-1-75	graphitic schist	Unnamed Pgvi	E. Prot.	39.30	1.08	26.50	3.15
CL-1-104	graphitic schist	Unnamed Pgvi	E. Prot.	44.80	0.93	17.10	14.90
CL-1-171	graphitic schist	Unnamed Pgvi	E. Prot.	51.30	0.81	19.40	7.59
CL-1-232	graphitic schist	Unnamed Pgvi	E. Prot.	51.30	1.03	20.00	5.26
CL-1-259	graphitic schist	Unnamed Pgvi	E. Prot.	52.60	0.94	19.90	6.48
MG-6-172	marble	Unnamed Pgvi	E. Prot.	8.16	0.12	3.08	6.23
MG-6-201	graphitic schist	Unnamed Pgvi	E. Prot.	58.70	0.71	19.40	5.65
MG-1-204	graphitic schist	Unnamed Pgvi	E. Prot.	59.70	0.91	19.00	4.00
MLCH-11-17	graphitic chert	Unnamed Pgvi	E. Prot.	65.30	0.69	11.90	8.76
MLCH-11-27	graphitic chert	Unnamed Pgvi	E. Prot.	40.00	0.46	7.18	30.70
MG-7-25	graphitic schist	Unnamed Pgvi	E. Prot.	41.90	1.47	17.10	21.20
MG-7-68	graphitic schist	Unnamed Pgvi	E. Prot.	44.20	0.40	9.01	31.70
MG-7-461	graphitic schist	Unnamed Pgvi	E. Prot.	50.70	0.92	22.60	6.89
MG-7-521	graphitic schist	Unnamed Pgvi	E. Prot.	60.10	0.72	15.00	6.85
MG-5-92	graphitic schist	Unnamed Pgvi	E. Prot.	50.40	1.63	15.50	15.90
MG-5-110	graphitic schist	Unnamed Pgvi	E. Prot.	44.60	0.58	12.20	22.40
MG-5-138	graphitic schist	Unnamed Pgvi	E. Prot.	43.30	1.24	13.30	19.70
MG-5-237	graphitic schist	Unnamed Pgvi	E. Prot.	51.30	1.53	13.60	14.40

Whole-rock Chemical Analyses continued

SAMPLE ID	UNIT LITHOLOGY	FORMATION	AGE	SiO2%	TiO2%	Al2O3%	Fe2O3 total%
MG-5-269	massive sulfide	Unnamed Pgvi	E. Prot.	33.90	0.37	6.91	41.50
MG-5-281	graphitic schist	Unnamed Pgvi	E. Prot.	41.70	1.70	15.70	21.80
MG-5-317	massive sulfide	Unnamed Pgvi	E. Prot.	37.20	0.30	6.07	36.90
MG-5-359	massive sulfide	Unnamed Pgvi	E. Prot.	24.80	0.28	5.30	52.90
MLCH-4-68	graphitic pyritic chert	Thomson Fm Pvt2	E. Prot	29.30	0.74	5.80	30.70
MLCH-4-80	massive sulfide	Thomson Fm Pvt2	E. Prot	22.40	0.47	5.98	27.20
MLCH-3-89	massive sulfide	Thomson Fm Pvt2	E. Prot	23.30	0.42	6.38	25.30
MLCH-2-103	massive sulfide	Thomson Fm Pvt2	E. Prot	23.10	0.40	5.99	24.90
A-2-631	graphitic schist	Glen Twsp	E. Prot	46.20	1.42	13.00	24.20
A-2-790	graphitic schist	Glen Twsp	E. Prot	49.70	2.35	15.80	11.20
A-2-917	graphitic schist	Glen Twsp	E. Prot	45.00	1.08	8.82	27.00
A-2-981	graphitic pyritic chert	Glen Twsp	E. Prot	33.20	0.45	3.88	37.30
A-5-830	graphitic schist	unnamed Pgvi	E. Prot	49.30	1.81	15.30	13.40
A-5-1010	graphitic schist	unnamed Pgvi	E. Prot	49.90	1.47	15.50	16.60
A-5-1169	graphitic schist	unnamed Pgvi	E. Prot	54.60	1.43	14.70	13.90
A-5-1301	graphitic schist	unnamed Pgvi	E. Prot	50.60	1.47	13.40	18.40
A-6-747	graphitic schist	Glen Twsp	E. Prot	39.50	1.63	14.60	25.20
A-6-915	graphitic pyritic chert	Glen Twsp	E. Prot	29.70	0.26	2.94	42.60
A-6-976	graphitic schist	Glen Twsp	E. Prot	41.70	0.41	9.24	27.80
A-6-1120	graphitic schist	Glen Twsp	E. Prot	46.50	0.29	6.92	32.20
46-25-BM-3-111	graphitic pyritic chert	Glen Twsp	E. Prot	42.60	0.20	4.13	33.10
46-25-BM-3-133	graphitic schist	Glen Twsp	E. Prot	46.50	0.38	8.96	27.90
KRCH-4-512	graphitic pyritic chert	unnamed Pvgi	E. Prot	44.80	1.10	23.80	11.00
H-G-4-78	massive sulfide	Glen Twsp	E. Prot	30.50	0.17	3.19	50.80
H-G-4-94	graphitic schist	Glen Twsp	E. Prot	44.60	0.40	9.51	26.50
H-1-334	graphitic schist	Thomson Fm Pvt2	E. Prot	57.20	0.94	19.70	8.48
46-25-MN-64-94	massive sulfide	Glen Twsp	E. Prot	33.30	0.25	5.05	36.70
46-25-MN-64-148	massive sulfide	Glen Twsp	E. Prot	21.30	0.30	5.96	54.50
46-25-MN-64-185	massive sulfide	Glen Twsp	E. Prot	30.00	0.24	4.64	49.10
ML-49c-378	graphitic pyritic chert	Denham Fm	E. Prot	64.40	0.22	3.63	3.08

Whole-rock Chemical Analyses continued

SAMPLE ID	Fe2O3%	FeO%	MnO%	MgO%	CaO%	Na2O%	K2O%	P2O5%	LOI
47-19-15	3.68	4.80	0.06	2.39	0.04	0.04	3.23	0.04	5.08
AB-2-103-1	2.56	2.80		2.34	0.03	0.14	5.44	0.04	7.62
AB-24A-423	6.18	3.40		1.83	0.02	0.36	5.42	0.04	7.70
AB-27-210-1	10.77	1.20		0.00	0.11	0.55	0.17	0.23	49.00
Arrow-1	20.41	0.80		0.42	0.18	0.34	1.84	0.16	32.70
EL-1-22	3.60	1.60	0.00	1.98	0.02	0.17	5.98	0.02	9.85
EL-1-57	7.96	2.20		1.65	0.04	0.24	5.42	0.04	17.20
EL-1-74	2.70	1.50	0.00	2.02	0.04	0.21	7.91	0.05	8.31
EL-1-121	4.21	2.80	0.00	2.34	0.00	0.28	8.69	0.03	8.31
EL-1-188	7.65	3.10	0.02	1.88	0.06	0.26	5.69	0.05	9.23
LV-3-385	2.68	4.10		2.81	0.49	1.69	3.62	0.17	5.00
Arrow-2	24.81	0.80		0.57	0.18	0.00	1.97	0.16	33.80
Arrow-3	20.92	0.70		0.52	0.02	0.00	2.23	0.04	38.10
Arrow-4	24.12	0.70		0.57	0.14	0.00	2.27	0.13	36.00
CL-1-75			0.08	4.06	2.96	0.30	8.75	0.09	13.50
CL-1-104				2.17	0.33	0.29	4.94	0.06	14.90
CL-1-171				2.03	0.26	0.18	5.88	0.06	12.90
CL-1-232				2.08	0.26	0.24	6.09	0.06	13.80
CL-1-259				1.89	0.26	0.22	6.17	0.06	11.70
MG-6-172			0.45	15.30	25.40	0.06	1.14	0.02	38.60
MG-6-201				1.76	0.25	0.24	6.33	0.05	7.08
MG-1-204				2.69	0.35	0.16	5.37	0.14	7.85
MLCH-11-17				1.40	0.23	0.18	3.06	0.09	8.47
MLCH-11-27				0.88	0.26	0.24	1.75	0.06	19.20
MG-7-25				1.39	0.36	0.58	4.68	0.13	10.80
MG-7-68				1.47	0.35	0.91	2.67	0.16	9.54
MG-7-461				2.28	0.35	0.28	7.07	0.06	8.92
MG-7-521				1.76	0.25	0.23	4.82	0.06	10.50
MG-5-92				0.83	0.47	0.32	3.80	0.03	11.80
MG-5-110			0.10	1.54	0.41	0.30	3.16	0.08	15.10
MG-5-138			0.28	3.50	2.41	0.29	2.92	0.23	12.90
MG-5-237				2.27	1.88	1.33	3.32	0.21	10.20

Whole-rock Chemical Analyses continued

SAMPLE ID	Fe2O3%	FeO%	MnO%	MgO%	CaO%	Na2O%	K2O%	P2O5%	LOI
MG-5-269				1.41	0.30	0.37	1.28	0.05	14.50
MG-5-281				1.90	1.52	2.48	3.23	0.10	9.38
MG-5-317				1.17	0.94	0.38	1.55	0.39	14.90
MG-5-359				1.22	0.95	0.35	1.33	0.11	12.90
MLCH-4-68				2.53	0.42	0.13	0.26	0.19	29.50
MLCH-4-80				0.96	0.30	0.11	1.60	0.15	40.60
MLCH-3-89				0.88	0.34	0.06	2.17	0.22	41.20
MLCH-2-103				0.77	0.45	0.10	2.12	0.21	41.80
A-2-631				1.70	0.67	1.64	3.66	0.16	7.23
A-2-790			0.11	2.37	1.53	3.89	3.09	0.33	9.54
A-2-917			0.59	2.77	1.89	0.93	2.29	0.17	9.54
A-2-981				2.80	6.55	0.09	0.14	0.25	13.60
A-5-830				3.52	0.33	0.11	3.79	0.21	12.40
A-5-1010			0.15	2.88	0.54	0.40	3.26	0.33	9.16
A-5-1169			0.15	2.49	0.40	0.59	3.22	0.20	8.31
A-5-1301			0.39	2.98	0.36	0.12	2.38	0.16	9.70
A-6-747				2.04	0.46	3.87	2.33	0.17	10.30
A-6-915			1.41	2.55	3.93	0.07	1.11	0.19	15.20
A-6-976				2.23	0.50	0.97	3.29	0.10	13.60
A-6-1120				1.56	1.14	1.17	2.09	0.16	7.93
46-25-BM-3-111			0.12	1.50	0.36	0.07	1.03	0.19	16.80
46-25-BM-3-133				2.20	0.94	1.05	2.34	0.34	9.54
KRCH-4-512			0.11	3.63	2.67	0.29	5.51	0.20	6.00
H-G-4-78			0.14	1.16	0.22	0.12	1.34	0.11	11.80
H-G-4-94			0.86	2.59	0.27	0.95	3.17	0.09	11.40
H-1-334				2.52	0.28	0.76	4.31	0.10	5.85
46-25-MN-64-94				0.90	0.28	0.10	1.85	0.09	21.20
46-25-MN-64-148				1.45	0.14	0.12	1.85	0.07	13.80
46-25-MN-64-185				1.27	0.28	0.24	1.67	0.15	12.10
ML-49c-378			0.13	2.46	1.99	0.10	0.91	0.04	22.30

Whole-rock Chemical Analyses continued

SAMPLE ID	TOTAL%	C% TOTAL	C% GRAPH	H2O+%	H2O-%	CO2%	S%	log(R)	Ag ppm
47-19-15	99.07	0.81	0.81	3.20	0.30	0.01	0.04		
AB-2-103-1	99.06	2.33	2.33	2.20	0.20	0.00	0.57	5.57	0
AB-24A-423	99.65	1.52	1.47	2.60	0.10	0.18	1.91	5.69	1
AB-27-210-1	96.53	44.40	44.40	2.20	1.70	0.00	3.94	0.67	6
Arrow-1	99.75	20.80	20.80	1.50	0.70	0.00	10.60	1.71	0
EL-1-22	99.46	4.81	4.81	1.70	0.20	0.00	1.96	4.34	
EL-1-57	100.13	10.00	10.00	1.30	0.10	0.00	3.70	3.31	0
EL-1-74	100.08	3.34	3.32	1.90	0.20	0.06	0.81	5.51	
EL-1-121	99.60	2.28	2.21	2.30	0.30	0.27	1.28	6.21	
EL-1-188	99.78	2.85	2.85	1.40	0.10	0.00	3.12	5.05	
LV-3-385	99.16	1.30	1.26	2.70	0.20	0.15	0.69	5.50	0
Arrow-2	97.27	21.50	21.50				13.50		0
Arrow-3	95.51	26.10	26.10				12.20		0
Arrow-4	98.98	23.10	23.10				12.70		0
CL-1-75	99.77	7.57	6.34			4.52	0.02	3.10	0
CL-1-104	100.42	6.51	6.41			0.36	6.70	2.80	0.5
CL-1-171	100.41	7.33	7.33			0.01	2.70	2.44	0
CL-1-232	100.12	9.74	9.66			0.28	0.74	2.24	0
CL-1-259	100.22	6.56	6.48			0.31	2.00	3.29	0
MG-6-172	98.56	12.40	1.65			39.40	0.08	4.57	0
MG-6-201	100.17	2.18	2.18			0.00	2.20	5.89	0
MG-1-204	100.17	4.36	4.33			0.11	0.05	5.43	0
MLCH-11-17	100.08	3.81	3.77			0.15	2.40	4.84	0
MLCH-11-27	100.73	3.05	3.05			0.01	2.10	4.22	0
MG-7-25	99.61	4.11	3.95			0.58	8.70	3.46	0
MG-7-68	100.41	2.43	2.38			0.17	15.00	2.79	0
MG-7-461	100.07	4.75	4.68			0.25	1.40	4.20	0
MG-7-521	100.29	6.68	6.68			0.01	2.10	2.91	0
MG-5-92	100.68	3.50	2.95			2.03	6.10	4.77	0
MG-5-110	100.47	3.16	2.55			2.25	11.00	5.25	0
MG-5-138	100.07	4.28	2.50			6.53	4.60	5.62	0
MG-5-237	100.04	3.23	2.36			3.18	5.20	5.77	0

Whole-rock Chemical Analyses continued

SAMPLE ID	TOTAL%	C% TOTAL	C% GRAPH	H2O+%	H2O-%	CO2%	S%	log(R)	Ag ppm
MG-5-269	100.59	4.04	3.58			1.69	20.00	2.18	0
MG-5-281	99.51	3.34	2.81			1.93	7.20	3.98	0
MG-5-317	99.80	2.34	1.83			1.88	19.00	4.17	0
MG-5-359	100.14	2.66	2.37			1.07	26.00	2.00	0
MLCH-4-68	99.57						9.75	3.44	0
MLCH-4-80	99.77						19.95	0.91	0
MLCH-3-89	100.27						18.93	1.73	0
MLCH-2-103	99.84						16.44	2.21	0
A-2-631	99.88						5.31	3.71	0
A-2-790	99.91						1.86	2.30	0
A-2-917	100.08						6.03	2.48	0
A-2-981	98.26						7.35	2.77	0
A-5-830	100.17						2.32	2.10	0
A-5-1010	100.19						0.82	2.02	0
A-5-1169	99.99						0.86	2.60	0
A-5-1301	99.96						0.78	2.55	0
A-6-747	100.10						5.82	2.10	0
A-6-915	99.96						12.42	1.57	0
A-6-976	99.84						12.03	3.05	0
A-6-1120	99.96						10.53	2.73	0
46-25-BM-3-111	100.10						13.83	6.56	0
46-25-BM-3-133	100.15						6.30	3.91	0
KRCH-4-512	99.11						0.00	6.85	0
H-G-4-78	99.55						22.47	4.24	0
H-G-4-94	100.34						5.40	3.34	0
H-1-334	100.14						0.27	6.36	0
46-25-MN-64-94	99.72						17.52	4.61	0
46-25-MN-64-148	99.49						21.30	2.06	0
46-25-MN-64-185	99.69						17.76	2.64	0
ML-49c-378	99.26						0.30	3.16	0

Whole-rock Chemical Analyses continued

SAMPLE ID	As ppm	Au ppb	B ppm	Ba ppm	Be ppm	Bi ppm	Br ppm	Cd ppm	Cl ppm	Co ppm	Cr ppm
47-19-15				604					0		109
AB-2-103-1	15	7	100	660	2		0.9	0	0	14	150
AB-24A-423	4	15	270	442	4		1.3	0	0	22	170
AB-27-210-1	180	27	0	369	3		3.3	2	700	12	19
Arrow-1	240	150	20	354	3		2.3	4	100	25	83
EL-1-22				956					0		171
EL-1-57	2	9	130	790	2		1.5	0	0	16	130
EL-1-74				1260					0		183
EL-1-121				1600					0		191
EL-1-188				943					0		158
LV-3-385	29	8	90	654	1		1.7	2	0	24	150
Arrow-2	320	350	40	370	5	2.2		5		33	70
Arrow-3	280	160	20	402	5	0.8		0		17	64
Arrow-4	320	180	30	394	5	1.5		1		23	76
CL-1-75	0	4	850	646	5	0		0		5	160
CL-1-104	53	7	830	613	5	7		0		54	250
CL-1-171	4	1	360	534	0	0		0		25	230
CL-1-232	0	0	560	614	0	0		1		10	310
CL-1-259	1	3	420	579	0	0		0		21	260
MG-6-172	0	0	40	18	0	0		0		14	32
MG-6-201	1	0	170	859	0	0		0		26	220
MG-1-204	0	0	120	880	0	0		0		5	180
MLCH-11-17	16	4	110	749	0	0		0		36	170
MLCH-11-27	250	47	90	623	5	0		0		59	230
MG-7-25	1	2	240	993	5	0		0		29	130
MG-7-68	0	18	170	339	10	0		7		23	210
MG-7-461	0	0	260	1100	5	0		0		20	210
MG-7-521	0	0	200	500	5	0		0		21	220
MG-5-92	0	3	110	591	5	0		0		49	270
MG-5-110	0	0	40	646	10	0		0		39	280
MG-5-138	0	4	30	602	5	0		0		46	220
MG-5-237	0	0	30	690	5	0		0		22	140

Whole-rock Chemical Analyses continued

SAMPLE ID	As ppm	Au ppb	B ppm	Ba ppm	Be ppm	Bi ppm	Br ppm	Cd ppm	Cl ppm	Co ppm	Cr ppm
MG-5-269	4	0	1500	447	10	0		0		120	200
MG-5-281	0	0	220	667	5	0		0		5	110
MG-5-317	75	4	140	369	10	0		15		54	180
MG-5-359	0	2	70	410	15	0		0		36	130
MLCH-4-68	360	140	20	213	5	0		4	213	72	150
MLCH-4-80	290	120	10	272	5	0		11	186	31	140
MLCH-3-89	300	160	30	293	10	0		2	411	34	150
MLCH-2-103	300	130	30	354	10	0		8	237	31	140
A-2-631	0	19	20	1360	10	0		0	0	58	89
A-2-790	0	4	10	1100	5	0		0	0	19	110
A-2-917	0	9	0	467	10	0		0	0	54	170
A-2-981	0	11	0	100	10	0		0	0	28	86
A-5-830	6	6	50	697	5	0		0	186	27	79
A-5-1010	0	6	30	735	5	0		0	0	39	65
A-5-1169	1	7	30	643	0	0		0	0	31	110
A-5-1301	0	2	30	478	5	0		0	0	37	110
A-6-747	3	8	20	896	10	0		0	0	65	92
A-6-915	1	47	0	197	10	0		0	0	25	76
A-6-976	110	9	0	333	10	0		0	0	49	170
A-6-1120	98	11	130	383	10	0		4	0	17	170
46-25-BM-3-111	2	6	30	206	10	0		0	0	52	170
46-25-BM-3-133	5	16	50	481	5	0		0	0	47	120
KRCH-4-512	60	6	70	1290	5	0		0	0	48	200
H-G-4-78	100	25	20	218	15	0		0	0	48	160
H-G-4-94	15	11	50	389	10	0		0	0	13	110
H-1-334	11	1	110	600	0	0		1	0	19	160
46-25-MN-64-94	8	5	10	447	10	10		0	0	35	280
46-25-MN-64-148	3	3	20	492	15	21		0	0	24	130
46-25-MN-64-185	5	9	10	311	10	8		0	0	24	110
ML-49c-378	16	8	0	501	0	0		0	216	23	500

Whole-rock Chemical Analyses continued

SAMPLE ID	Cs ppm	Cu ppm	Ga ppm	Ge ppm	Hf ppm	In ppm	Ir ppb	Li ppm	Mn ppm	Mo ppm	Nb ppm
47-19-15											28
AB-2-103-1	6.2	78		0	3.7				120	6	0
AB-24A-423	8	120		0	3.5				100	6	21
AB-27-210-1	0	2500		0	1.5		9		50	210	13
Arrow-1	4.2	150		0	1.3		27		450	180	20
EL-1-22											0
EL-1-57	5.2	87		0	2.7				34	39	20
EL-1-74											13
EL-1-121											31
EL-1-188											22
LV-3-385	4.2	100		0	3.9				280	10	14
Arrow-2	6	48	7	0	2	0		10	460	215	21
Arrow-3	5	36	6	0	2	0		10	400	245	15
Arrow-4	6	33	7	0	2	0		0	140	214	21
CL-1-75	4	29		10	5	0		0	800	12	25
CL-1-104	4	150		0	4	0		0	86	13	20
CL-1-171	5	130		0	2	0		0	32	13	15
CL-1-232	5	84		10	3	0		0	46	35	23
CL-1-259	4	100		0	3	0		0	22	9	30
MG-6-172	1	7.5		0	0	0		0	4500	0	0
MG-6-201	3	110		0	2	0		0	40	4	0
MG-1-204	4	71		0	5	0		0	140	6	28
MLCH-11-17	3	320		10	3	0		0	68	9	0
MLCH-11-27	4	210		0	2	0		0	28	15	0
MG-7-25	2	170		0	6	0		0	160	19	36
MG-7-68	2	280		0	1	0		0	50	18	18
MG-7-461	6	96		10	3	0		0	52	11	15
MG-7-521	3	140		0	3	0		0	40	11	22
MG-5-92	1	180		0	5	0		0	500	17	35
MG-5-110	0	190		30	2	0		0	1000	23	20
MG-5-138	2	150		10	3	0		0	2800	17	28
MG-5-237	0	80		10	4	0		0	390	6	42

Whole-rock Chemical Analyses continued

SAMPLE ID	Cs ppm	Cu ppm	Ga ppm	Ge ppm	Hf ppm	In ppm	Ir ppb	Li ppm	Mn ppm	Mo ppm	Nb ppm
MG-5-269	0	300		20	1	0		0	170	38	21
MG-5-281	2	150		20	6	0		0	260	17	56
MG-5-317	1	270		10	1	0		0	250	12	29
MG-5-359	1	780		0	1	0		0	130	16	17
MLCH-4-68	1	420		10	2	0		40	260	140	30
MLCH-4-80	3	30		0	2	0		30	86	230	16
MLCH-3-89	4	76		0	1	0		30	64	230	20
MLCH-2-103	4	89		0	1	0		20	70	220	13
A-2-631	3	130		10	7	0		40	350	18	67
A-2-790	3	55		0	7	0		40	1100	27	79
A-2-917	6	97		0	3	0		30	5900	32	12
A-2-981	1	150		0	1	0		10	100	27	20
A-5-830	4	100		10	8	0		80	270	35	71
A-5-1010	4	130		0	5	0		100	1500	20	32
A-5-1169	4	89		0	5	0		90	1500	22	44
A-5-1301	3	140		0	4	0		120	3900	14	54
A-6-747	1	160		0	6	0		30	190	39	77
A-6-915	11	160		0	1	0		20	14100	21	32
A-6-976	13	55		0	2	0		50	230	31	18
A-6-1120	6	220		0	1	0		50	210	22	0
46-25-BM-3-111	1	127		0	1	0		30	1200	23	0
46-25-BM-3-133	4	120		0	2	0		40	330	22	21
KRCH-4-512	8	240		0	6	0		70	1100	22	19
H-G-4-78	2	110		0	1	0		20	1400	31	0
H-G-4-94	7	54		0	2	0		40	8600	20	28
H-1-334	6	53		0	5	0		90	500	10	28
46-25-MN-64-94	2	210		0	1	0		20	380	39	21
46-25-MN-64-148	2	250		30	2	0		40	88	48	28
46-25-MN-64-185	5	210		10	1	0		30	230	36	37
ML-49c-378	1	390		0	1	0		0	1300	88	0

Whole-rock Chemical Analyses continued

SAMPLE ID	Ni ppm	Pb ppm	Pd ppb	Pt ppb	Rb ppm	Sb ppm	Sc ppm	Se ppm	Sn ppm	Sr ppm	Ta ppm
47-19-15					106					16	
AB-2-103-1	73	10			186	1.6	27.8	0		33	0.8
AB-24A-423	110	28			238	1.4	30.4	2		99	1
AB-27-210-1	230	34			0	64	5.88	98		162	0
Arrow-1	220	60			84	36	13.3	25		17	0
EL-1-22					174					29	
EL-1-57	210	18			181	0.8	22.7	13		20	0.6
EL-1-74					216					37	
EL-1-121					237					41	
EL-1-188					151					25	
LV-3-385	85	26			144	5.2	22.4	5		74	0
Arrow-2	270	72	17	10	0	40		0	0	11	0
Arrow-3	190	50	20	10	0	40		0	0	0	0
Arrow-4	230	64	23	10	0	40		0	0	0	0
CL-1-75	21	4	2	0	216	0	26.7	0	0	96	2
CL-1-104	150	52	8	0	159	0.3	19.7	7	0	58	0
CL-1-171	220	8	12	0	196	0.5	27.4	6	0	66	0
CL-1-232	190	4	6	0	224	0.4	32.7	3	0	53	0
CL-1-259	140	4	5	0	219	0.7	31.5	5	14	46	1
MG-6-172	22	0	0	0	49	0	4.6	0	0	223	0
MG-6-201	87	4	4	0	204	0.2	23	0	0	45	0
MG-1-204	34	2	5	10	195	0	27.9	0	0	50	0
MLCH-11-17	76	2	5	0	154	0.9	20.1	4	0	24	0
MLCH-11-27	160	38	3	0	92	10	11.6	3	0	33	0
MG-7-25	79	14	6	0	163	0.4	31.7	0	0	89	3
MG-7-68	120	26	9	0	123	0.6	12.1	6	0	80	0
MG-7-461	82	4	5	0	236	0.2	26.7	0	12	46	1
MG-7-521	130	8	7	0	154	0.3	21.4	4	0	26	1
MG-5-92	220	6	4	10	125	0	29.3	3	0	47	2
MG-5-110	180	30	5	0	104	0	15.5	4	0	19	0
MG-5-138	93	4	8	10	107	0	27	0	0	27	1
MG-5-237	60	4	3	10	113	0.6	27.9	0	0	131	2

Whole-rock Chemical Analyses continued

SAMPLE ID	Ni ppm	Pb ppm	Pd ppb	Pt ppb	Rb ppm	Sb ppm	Sc ppm	Se ppm	Sn ppm	Sr ppm	Ta ppm
MG-5-269	130	38	20	10	58	1.3	13.5	6	0	44	0
MG-5-281	83	8	3	0	118	0.6	29.5	0	0	216	2
MG-5-317	160	24	25	10	66	2.2	8.1	6	0	45	0
MG-5-359	230	18	10	10	50	1.8	8.3	5	0	40	1
MLCH-4-68	320	96	12	10	0	55	11.1	19	0	18	0
MLCH-4-80	360	66	21	20	84	65	14	14	0	13	0
MLCH-3-89	390	52	18	0	113	53	13.9	10	0	19	0
MLCH-2-103	360	44	20	20	110	49	13.4	5	0	26	0
A-2-631	130	0	6	10	144	0.7	21	9	0	122	3
A-2-790	48	0	0	0	137	0.4	24.4	0	0	379	3
A-2-917	83	0	0	0	122	0.7	16.1	0	0	110	1
A-2-981	110	0	3	0	24	0.8	9.3	9	0	177	0
A-5-830	70	0	9	0	141	2.9	29.9	0	0	44	2
A-5-1010	53	0	4	0	127	0.8	28.7	0	0	26	1
A-5-1169	41	0	5	0	123	0.8	29.7	4	0	41	2
A-5-1301	60	0	18	0	119	0.7	25.1	0	0	22	1
A-6-747	140	0	6	0	94	1.1	24.3	14	0	176	3
A-6-915	100	38	7	0	100	3.8	7.4	7	0	47	0
A-6-976	98	14	7	0	256	9.9	12.6	6	0	18	0
A-6-1120	160	0	4	0	115	2.7	8.1	7	0	43	0
46-25-BM-3-111	134	0	9	0	58	0.5	7.4	7	0	0	0
46-25-BM-3-133	77	0	10	0	106	0.8	9.4	9	0	43	0
KRCH-4-512	140	0	9	0	199	0.9	34.1	0	0	80	0
H-G-4-78	170	0	4	0	94	3.4	6	8	0	0	0
H-G-4-94	67	0	10	0	185	4.3	11.5	0	0	16	0
H-1-334	82	8	3	0	174	0.2	16.8	0	0	87	0
46-25-MN-64-94	180	0	8	0	109	1.2	10.2	14	0	0	0
46-25-MN-64-148	210	18	0	0	0	2.3	11.4	16	0	0	0
46-25-MN-64-185	180	56	9	10	0	1.9	8.7	10	0	0	0
ML-49c-378	140	56	11	10	49	1.3	10	25	0	0	0

Whole-rock Chemical Analyses continued

SAMPLE ID	Th ppm	Tl ppm	U ppm	V ppm	W ppm	Y ppm	Zn ppm	Zr ppm	La ppm	Ce ppm	Nd ppm
47-19-15						0		121			
AB-2-103-1	11		8.3	310	6	27	73	132	36.8	61	25
AB-24A-423	14		2.9	190	3	0	65	133	43	67	24
AB-27-210-1	12		15.7	990	15	0	360	43	26.8	38	32
Arrow-1	4.2		38.7	1900	7	57	630	36	33.6	39	29
EL-1-22						16		79			
EL-1-57	12		8.3	310	2	32	110	91	33.3	52	21
EL-1-74						22		95			
EL-1-121						17		136			
EL-1-188						21		113			
LV-3-385	9		9.8	180	1	36	180	150	35.1	61	27
Arrow-2	5	7	74.6	1800	30	0	1300	48	32	42	30.5
Arrow-3	3	7	9.7	2100	14	0	120	76	34	44	30.3
Arrow-4	6	8	81.3	2100	11	0	300	67	33	43	30.2
CL-1-75	23		5.2	270	7	39	33	154	118	183	91
CL-1-104	17		6.5	200	3	23	86	121	54.9	80	32
CL-1-171	11		7.9	360	0	29	31	94	33.3	50	18
CL-1-232	16		12.7	560	3	23	160	115	45.5	72	29
CL-1-259	14		6.3	220	4	35	100	111	39	63	23
MG-6-172	2		0.7	20	0	0	62	0	9.7	17	6
MG-6-201	11		2.9	130	3	31	40	80	34.6	57	23
MG-1-204	8		12.9	350	0	39	160	211	43.3	79	81
MLCH-11-17	6		15	260	3	23	79	122	22.7	44	22
MLCH-11-27	4		7	190	0	0	210	54	16.8	32	12
MG-7-25	13		17.7	330	4	35	19	210	56.9	84	43
MG-7-68	6		13.2	350	0	0	1400	42	22.5	30	14
MG-7-461	14		8.8	350	4	19	42	123	51.2	75	28
MG-7-521	11		6.2	220	3	18	25	73	34	54	19
MG-5-92	9		7.7	390	6	38	36	192	49.3	79	32
MG-5-110	7		7.7	440	0	0	29	85	5.4	9	5
MG-5-138	4		7.4	670	0	16	170	89	22.8	39	15
MG-5-237	7		11.7	310	0	28	33	123	50.5	88	50

Whole-rock Chemical Analyses continued

SAMPLE ID	Th ppm	Tl ppm	U ppm	V ppm	W ppm	Y ppm	Zn ppm	Zr ppm	La ppm	Ce ppm	Nd ppm
MG-5-269	3		13.4	630	3	0	23	42	15.1	24	17
MG-5-281	9		11.2	360	0	30	17	203	39.4	58	29
MG-5-317	3		11.8	420	3	0	3300	44	21	30	25
MG-5-359	2		7.9	390	0	0	110	36	12.3	18	8
MLCH-4-68	3		57.9	780	5	0	1500	88	21.1	34	25
MLCH-4-80	4		75.1	2300	9	55	2000	87	30.5	38	39
MLCH-3-89	4		69.9	2500	8	56	790	67	23.9	32	35
MLCH-2-103	4		68	2300	6	50	1600	87	24.5	37	26
A-2-631	8		12.9	260	5	10	240	324	43.8	74	32
A-2-790	8		16	360	4	52	150	355	41.5	66	33
A-2-917	4		10.2	500	0	23	250	146	19.2	35	17
A-2-981	2		7.3	300	0	0	190	72	17.9	36	20
A-5-830	12		16.2	370	0	36	74	348	64.8	110	54
A-5-1010	7		13.4	450	0	22	140	218	48.2	84	50
A-5-1169	5		9.4	360	0	26	100	180	36.6	65	33
A-5-1301	6		11.2	390	0	23	110	202	42.3	71	38
A-6-747	9		19.9	310	0	31	360	330	50.4	81	43
A-6-915	2		6.3	330	0	18	140	74	17.6	32	21
A-6-976	4		13.4	510	0	0	200	69	17.5	29	16
A-6-1120	3		7.4	460	0	0	750	48	12.6	20	9
46-25-BM-3-111	2		9.2	420	0	0	259	49	10.7	17	11
46-25-BM-3-133	4		7.6	310	0	15	380	65	18.7	30	15
KRCH-4-512	11		3.7	240	0	36	100	217	38.8	81	36
H-G-4-78	2		7.5	400	0	0	470	64	8.4	14	10
H-G-4-94	5		8.9	360	0	21	110	91	17.8	29	10
H-1-334	8		3.4	180	0	15	79	180	35.6	65	31
46-25-MN-64-94	3		13.5	620	3	0	74	70	11.3	20	11
46-25-MN-64-148	3		16.9	750	7	0	28	87	12.4	23	8
46-25-MN-64-185	2		12.6	500	0	0	64	53	10.8	21	13
ML-49c-378	2		54.8	2000	8	57	42	26	13	20	17

Whole-rock Chemical Analyses continued

SAMPLE ID	Sm ppm	Eu ppm	Gd ppm	Tb ppm	Dy ppm	Er ppm	Yb ppm	Lu ppm
47-19-15								
AB-2-103-1	4.47	1.3		0.6			2.2	0.37
AB-24A-423	4.36	1.17		0.4			2.05	0.35
AB-27-210-1	6.95	2.13		0.7			3.46	0.69
Arrow-1	5.41	1.52		0.7			6.45	1.46
EL-1-22								
EL-1-57	3.81	1.05		0.4			2.62	0.47
EL-1-74								
EL-1-121								
EL-1-188								
LV-3-385	5.12	1.56		0.7			2.73	0.5
Arrow-2	5.3	1.4	4.3		4.4	3.2		0.9
Arrow-3	4.9	1.1	2.7		1.1	0.5		0.3
Arrow-4	5.2	1.4	4.7		4.5	3.3		1
CL-1-75	12	2.6		1.1			2	0.4
CL-1-104	5.9	0.8					2.6	0.5
CL-1-171	3.5	0.7					1.8	0.4
CL-1-232	5	1.4		0.7			3.1	0.7
CL-1-259	4.3	1.2					3.1	0.5
MG-6-172	1.1	0.7					0.8	0.1
MG-6-201	4.1	1					1.5	0.3
MG-1-204	6.8	1.7		0.9			3.8	0.7
MLCH-11-17	4	1.1		0.5			2	0.4
MLCH-11-27	2.4	0.7					1.3	0.3
MG-7-25	7.1	1.7		0.8			2.9	0.5
MG-7-68	2.8	0.8					1.6	0.4
MG-7-461	5.2	1.3		0.9			2.4	0.5
MG-7-521	4	1		0.6			2.1	0.4
MG-5-92	6.5	2.3		0.9			2.4	0.5
MG-5-110	1.2	0.5					1.2	0.3
MG-5-138	3.4	1					2.1	0.5
MG-5-237	6.9	2		0.7			2	0.4

Whole-rock Chemical Analyses continued

SAMPLE ID	Sm ppm	Eu ppm	Gd ppm	Tb ppm	Dy ppm	Er ppm	Yb ppm	Lu ppm
MG-5-269	2.2	0.6					2.3	0.6
MG-5-281	5.2	1.4		0.9			2.7	0.6
MG-5-317	3	1.1					1.5	0.4
MG-5-359	1.6	0.6					0.9	0.3
MLCH-4-68	4.4	1.2		0.6			3.6	0.6
MLCH-4-80	4.5	1.5		0.7			6.5	2.2
MLCH-3-89	4.3	1.6		1.4			6.6	2.1
MLCH-2-103	4.3	1.7		0.7			6.6	2.1
A-2-631	5.3	1.7		0.9			2.2	0.5
A-2-790	6.1	2.4		1.1			4.6	0.9
A-2-917	3.4	1		0.5			2.6	0.6
A-2-981	3.4	1.3		0			2.5	0.5
A-5-830	8.9	2.8		1.1			3.5	0.7
A-5-1010	6.7	2		0.8			2.5	0.6
A-5-1169	4.4	1.1		0			1.9	0.4
A-5-1301	5.4	1.8		0.7			2.7	0.5
A-6-747	6.8	2.1		0.9			3.1	0.7
A-6-915	2.8	0.9		0			2.5	0.5
A-6-976	2.5	0.8		0			1.8	0.5
A-6-1120	1.7	0.6		0			1.4	0.3
46-25-BM-3-111	1.8	0.7		0			1.5	0.4
46-25-BM-3-133	2.4	0.9		0			1.6	0.3
KRCH-4-512	6.4	1.4		0.9			2.8	0.5
H-G-4-78	1.3	0.6		0			1.3	0.3
H-G-4-94	2.2	0.6		0			1.4	0.4
H-1-334	3.7	0.9		0			1.2	0.2
46-25-MN-64-94	1.9	0.6		0			2	0.5
46-25-MN-64-148	2	0.6		0			1.9	0.6
46-25-MN-64-185	1.7	0.5		0			1.6	0.5
ML-49c-378	3	0.7		0.7			5.3	1.7

APPENDIX B

CHEMICAL ANALYSES OF THE HEAVY SULFIDES

(Blank cells, not analyzed for. The rock unit names under the heading FORMATION are from Southwick, Morey, and McSwiggen [1988]. Depth measured in feet.)

APPENDIX B

Chemical Analyses of the Heavy Sulfides

SAMPLE ID	SAMPLE TYPE	COUNTY	QUADRANGLE	TOWNSHIP	RANGE	SECTION	QUARTERS	DEPTH
AB-2-103-2-S	core	Carlton	Cromwell SE	47	19	7	CBBCAC	103
AB-27-210-1-S	core	Aitkin	Aitkin	47	26	19	DDDDDC	210
AB-27-210-2-S	core	Aitkin	Aitkin	47	26	19	DDDDDC	210
AB-24A-423-S	core	Crow Wing	Bay Lake	45	28	2	CDBCCC	423
Arrow-1-S	outcrop	Carlton	Barnum	48	18	32	BCBCC	0
EL-1-22-S	core	Carlton	Kettle River	46	20	8	D	22
EL-1-57-S	core	Carlton	Kettle River	46	20	8	D	57
EL-1-74-S	core	Carlton	Kettle River	46	20	8	D	74
EL-1-121-S	core	Carlton	Kettle River	46	20	8	D	121
EL-1-188-S	core	Carlton	Kettle River	46	20	8	D	188
LV-3-385-S	core	Cass	Longville	139	28	2	ABABAA	385

SAMPLE ID	UNIT LITHOLOGY	FORMATION	AGE	SiO2%	TiO2%	Al2O3%	Fe2O3 total%
AB-2-103-2-S	sulfide layer	Thomson Fm. Pvt	E. Prot.	2.70	0.39	0.91	
AB-27-210-1-S	siliceous graphite	Unnamed Pgs	E. Prot.	12.00	1.64	0.40	
AB-27-210-2-S	sulfide layer	Unnamed Pgs	E. Prot.	9.87	0.17	0.20	
AB-24A-423-S	graphitic slate	Unnamed Pgs	E. Prot.	11.40	12.90	8.72	
Arrow-1-S	graphitic argillite	Thomson Fm. Pvt	E. Prot.	3.85	0.77	1.13	
EL-1-22-S	graphtic phyllite	Unnamed Pgvi	E. Prot.	16.40	8.58	8.80	
EL-1-57-S	graphtic phyllite	Unnamed Pgvi	E. Prot.	5.91	3.28	2.77	
EL-1-74-S	graphtic phyllite	Unnamed Pgvi	E. Prot.	17.00	12.10	10.90	33.20
EL-1-121-S	graphtic phyllite	Unnamed Pgvi	E. Prot.	7.33	10.30	5.28	
EL-1-188-S	graphtic phyllite	Unnamed Pgvi	E. Prot.	7.84	4.79	4.77	
LV-3-385-S	graphitic slate	Virginia Pvt	E. Prot.	8.49	10.90	3.12	

Chemical Analyses of the Heavy Sulfides continued

SAMPLE ID	Fe2O3%	FeO%	MnO%	MgO%	CaO%	Na2O%	K2O%	P2O5%	LOI
AB-2-103-2-S	61.02	0.70	0.01	0.32	0.06	0.00	0.05	0.04	33.10
AB-27-210-1-S	51.14	4.10		0.18	0.04	0.06	0.03	0.43	28.70
AB-27-210-2-S	42.29	7.30		0.17	0.10	0.01	0.02	0.14	33.10
AB-24A-423-S	36.38	6.50	0.10	2.57	0.17	0.11	0.59	0.15	19.70
Arrow-1-S	56.71	0.80		0.16	0.31	0.00	0.33	0.30	34.30
EL-1-22-S	37.81	0.80	0.03	1.06	0.08	0.01	2.60	0.17	24.00
EL-1-57-S	54.14	0.50	0.00	0.43	0.17	0.00	0.75	0.19	31.90
EL-1-74-S			0.20	2.20	0.88	0.09	2.61	0.88	19.50
EL-1-121-S	40.98	7.40	0.12	1.02	0.11	0.03	0.89	0.31	25.70
EL-1-188-S	50.42	1.60	0.06	0.80	0.32	0.00	0.91	0.30	28.30
LV-3-385-S	40.04	1.40	0.02	0.57	3.39	0.08	0.56	2.64	23.80

SAMPLE ID	TOTAL%	S%	Ag ppm	As ppm	Au ppb	B ppm	Ba ppm	Be ppm	Bi ppm	Cd ppm
AB-2-103-2-S	99.3	31.10		6	98	0	179	10	2.2	
AB-27-210-1-S	98.7	16.50	11	1500	51	0	219	10	0	3
AB-27-210-2-S	93.4	27.20	5	15000	170	0	367	5	0	1
AB-24A-423-S	99.3	14.80		71	52	3200	130	10	6.6	
Arrow-1-S	98.7	33.50	0	1000	240	0	244	5	0.8	6
EL-1-22-S	100.3	20.00		6	74	490	421	5	3.8	
EL-1-57-S	100.0	30.10		18	36	380	252	10	8.3	
EL-1-74-S	66.4	15.40		6		2800	661	5		
EL-1-121-S	99.5	22.70		5		1700	230	5	6.9	
EL-1-188-S	100.1	28.90		6	72	800	259	10	5.8	
LV-3-385-S	95.0	22.90		2900		120	193	10		

Chemical Analyses of the Heavy Sulfides continued

SAMPLE ID	Nb ppm	Ni ppm	Pb ppm	Pd ppb	Pt ppb	Rb ppm	Sb ppm	Se ppm	Sn ppm	Sr ppm	Ta ppm
AB-2-103-2-S	37			6	10	0		0	0	0	1
AB-27-210-1-S	43	850	10	57	20	0	200	3	0	10	2
AB-27-210-2-S	36	230	50	11	10	0	260	6	0	0	0
AB-24A-423-S	236			22	20	0		0	0	0	1
Arrow-1-S	35	500	36	30	20	0	18	0	0	0	1
EL-1-22-S	194			66	40	0		0	0	0	0
EL-1-57-S	99			60	10	0		0	0	0	2
EL-1-74-S	317					0			0	0	
EL-1-121-S	275					0		0	0	0	2
EL-1-188-S	112			42	30	0		0	0	0	2
LV-3-385-S	170					0			0	35	

SAMPLE ID	Co ppm	Cr ppm	Cs ppm	Cu ppm	Ga ppm	Ge ppm	Hf ppm	In ppm	Li ppm	Mn ppm	Mo ppm
AB-2-103-2-S	31	74	0		0	0	0	0	0		2
AB-27-210-1-S	52	52	0	7700	2	0	2	0	0	58	332
AB-27-210-2-S	20	32	0	34000	0	0	0	0	0	24	83
AB-24A-423-S	112	246	0		8	10	15	0	30		94
Arrow-1-S	60	70	0	330	2	0	0	0	0	18	78
EL-1-22-S	241	231	2		9	20	16	0	0		29
EL-1-57-S	100	103	0		3	0	7	0	10		160
EL-1-74-S		246				30			20		
EL-1-121-S	182	192	0		5	0	31	0	0		17
EL-1-188-S	207	175	0		4	0	12	0	10		10
LV-3-385-S		83				20			0		

Chemical Analyses of the Heavy Sulfides continued

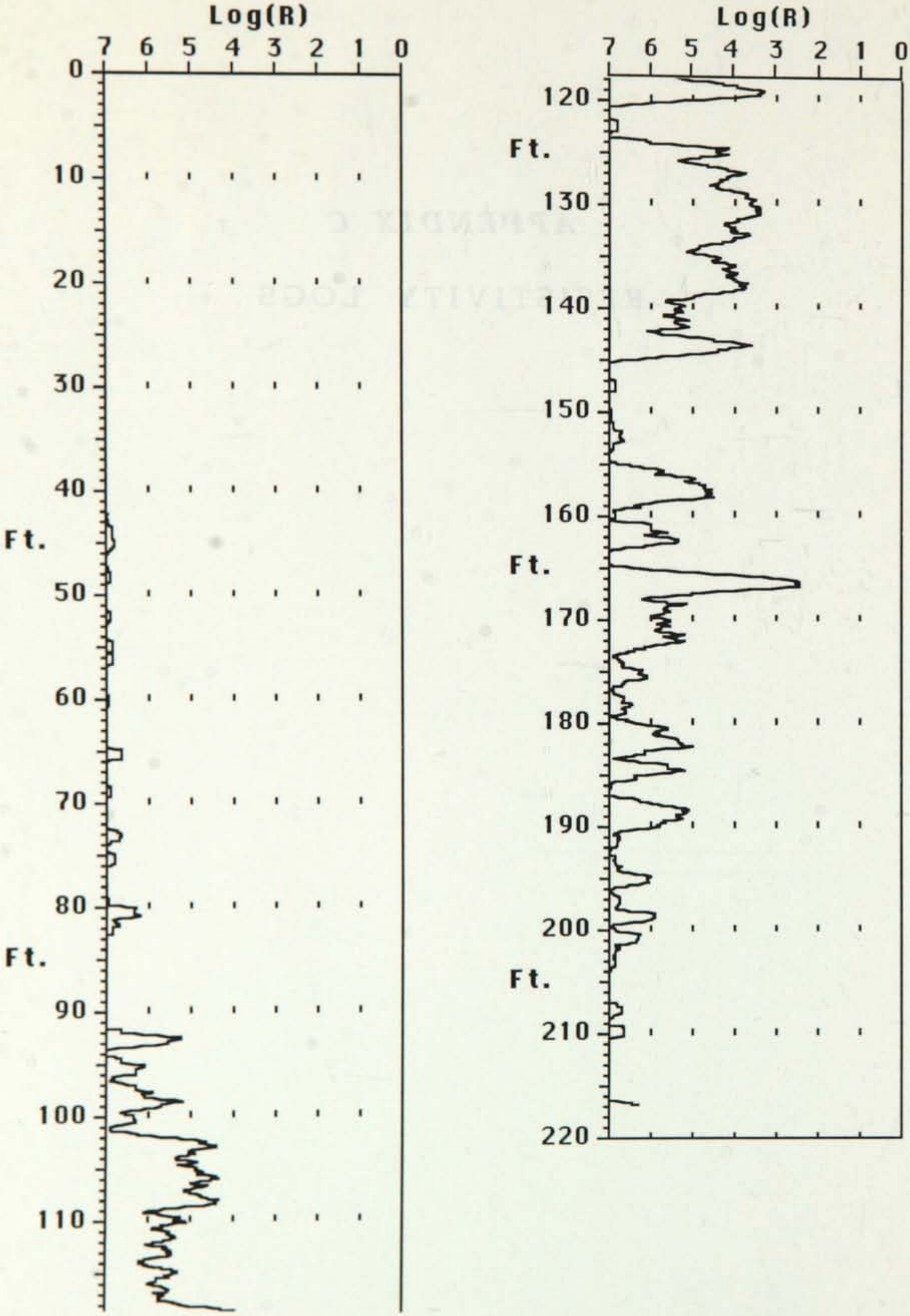
SAMPLE ID	Th ppm	Tl ppm	U ppm	V ppm	Y ppm	Zn ppm	Zr ppm	La ppm	Ce ppm	Nd ppm	Sm ppm
AB-2-103-2-S	2	0	1.1	10	0		0	18	35	19.3	3.5
AB-27-210-1-S	20	4	15.3	3600	0	1100	22	29	44	42.9	8.3
AB-27-210-2-S	7	26	7	280	0	260	0	21	29	29.4	5.6
AB-24A-423-S	69	3	12.6	210	0		259	305	537	258	39.2
Arrow-1-S	8	5	24.3	360	38	1600	0	95	122	90.8	14.2
EL-1-22-S	129	0	25.5	160	36		323	479	862	359	56.4
EL-1-57-S	55	0	21.1	100	0		282	198	354	157	24.2
EL-1-74-S				180	222		725				
EL-1-121-S	243	1	52	120	106		791	1000	1900	837	126
EL-1-188-S	75	2	13.9	70	0		167	285	530	225	35.6
LV-3-385-S				80	0		2060				

SAMPLE ID	Eu ppm	Gd ppm	Dy ppm	Er ppm	Lu ppm
AB-2-103-2-S	0.8	2.3	1	0	0.2
AB-27-210-1-S	2	5.1	2.2	1.3	0.4
AB-27-210-2-S	1.4	4.3	2.6	1.6	0.5
AB-24A-423-S	8.5	25.8	13.2	5.6	1.1
Arrow-1-S	3.1	8.6	3.4	1.9	0.5
EL-1-22-S	12.2	39.5	18.4	6.8	1.8
EL-1-57-S	5.4	16.3	8	3.5	0.9
EL-1-74-S					
EL-1-121-S	28.4	76.4	35.2	11.8	2.7
EL-1-188-S	7.7	23.2	11.3	4.2	1.1
LV-3-385-S					

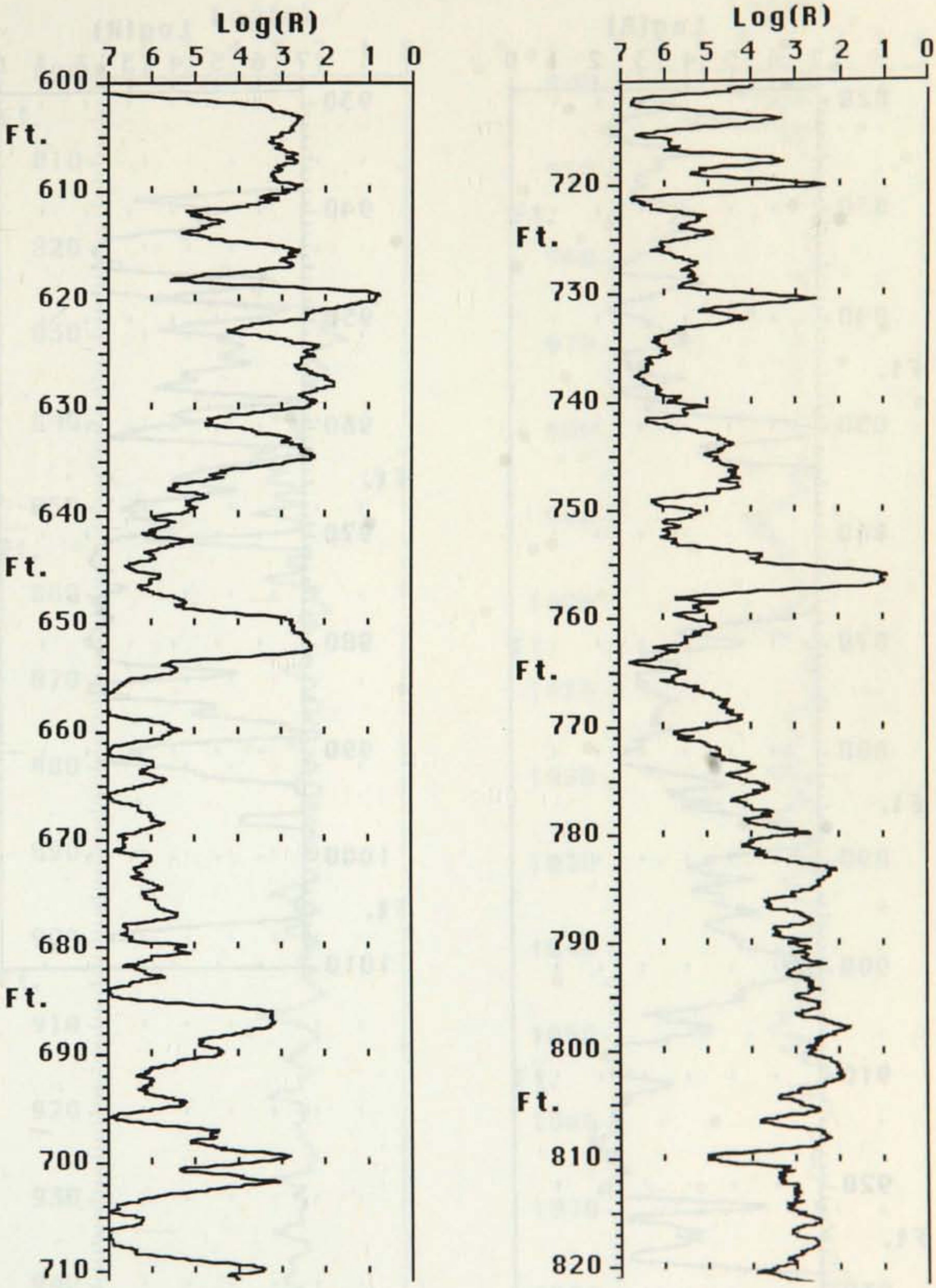
APPENDIX C

RESISTIVITY LOGS

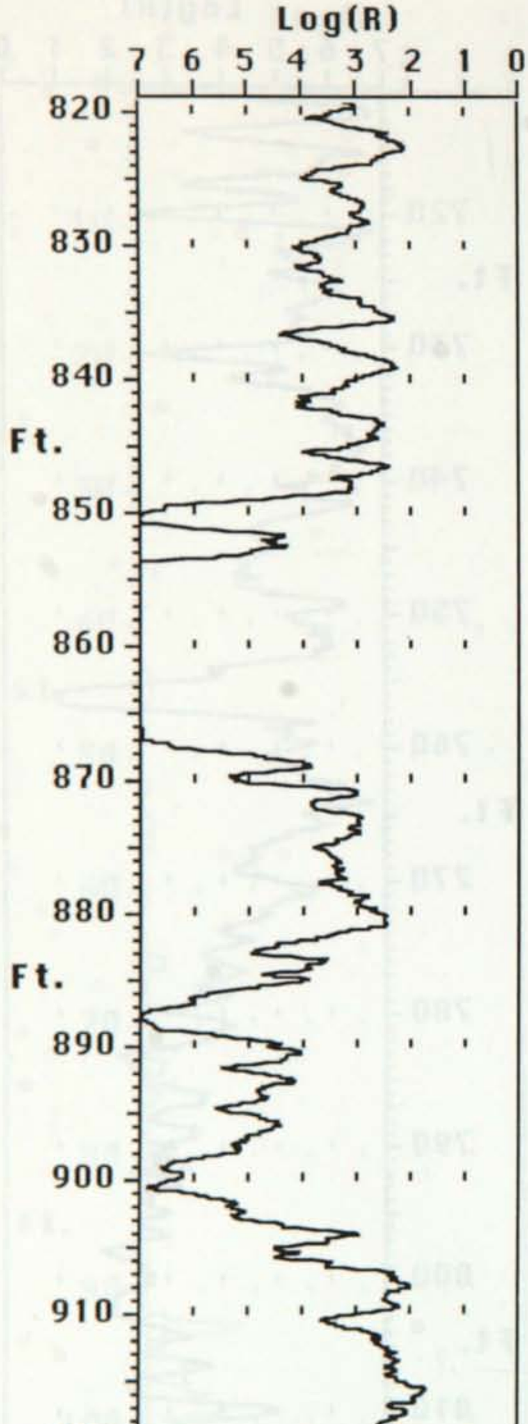
DRILL HOLE: **46–25–BM–3**; LOCATION: **Aitkin County, 46–25–15–ac**

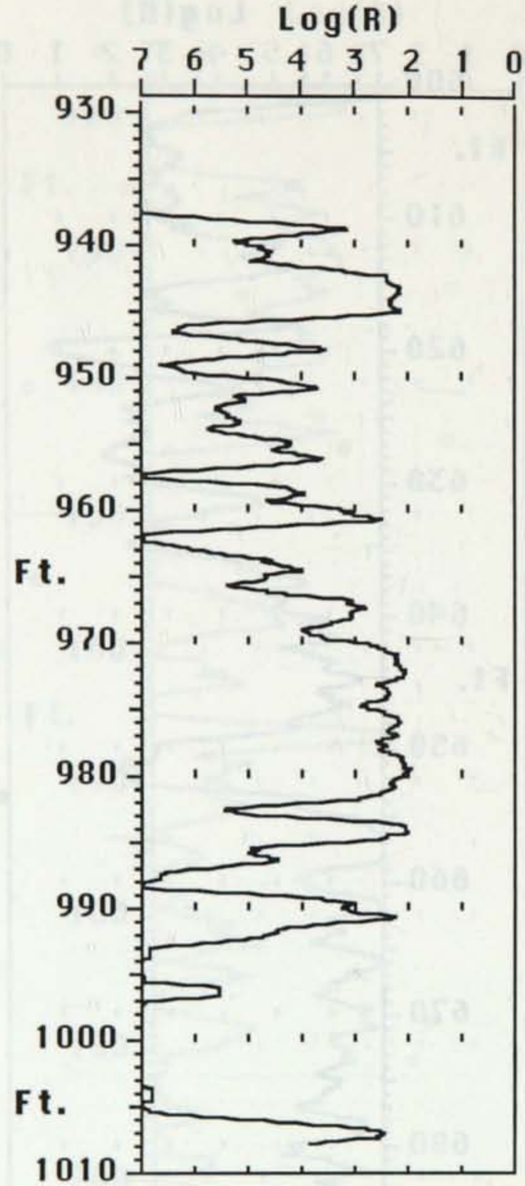


DRILL HOLE: **A–2**; LOCATION: **Aitkin County, 46–25–21–dd**

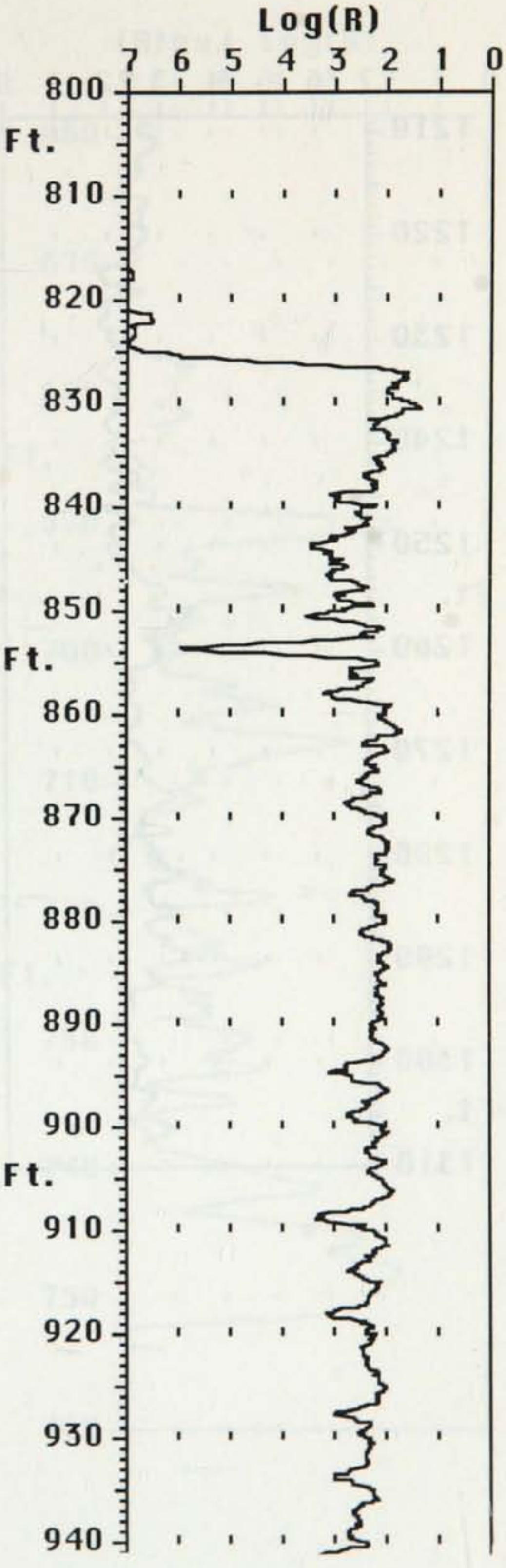


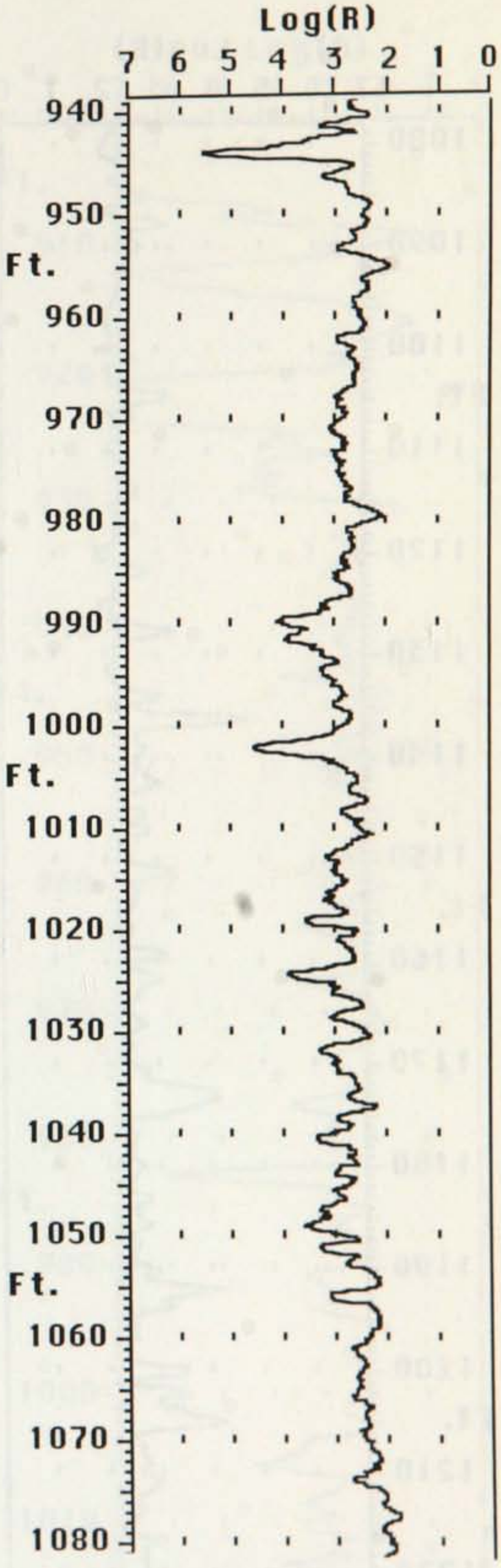
DRILL HOLE A–2 CONTINUED



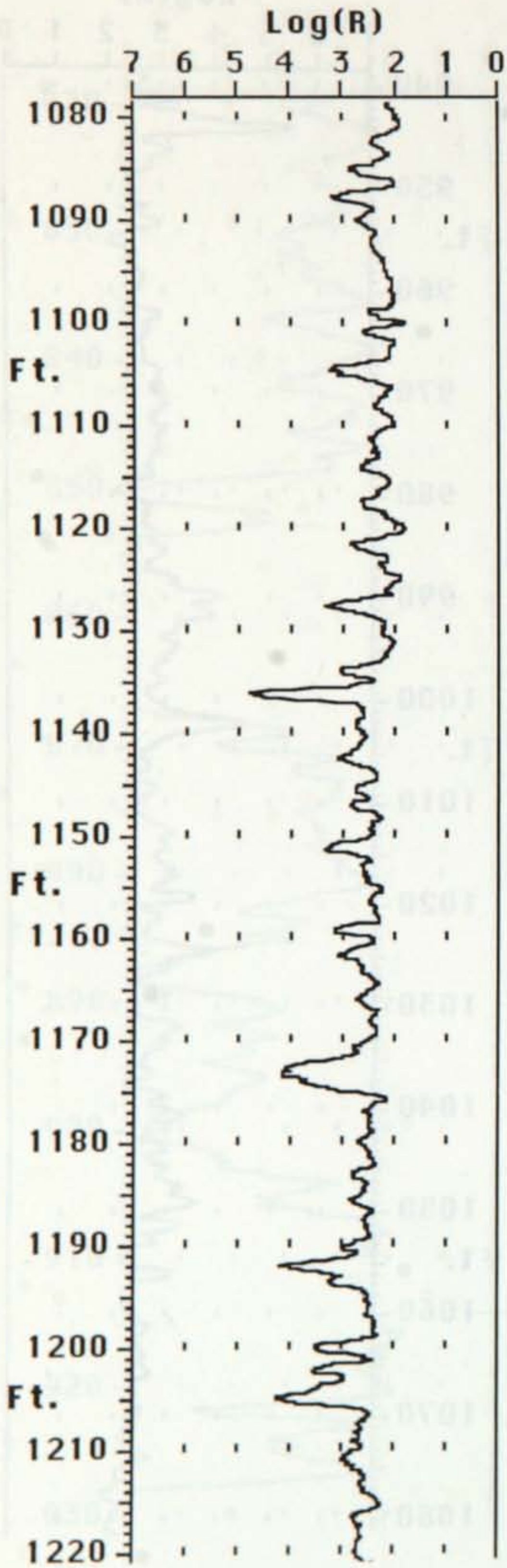


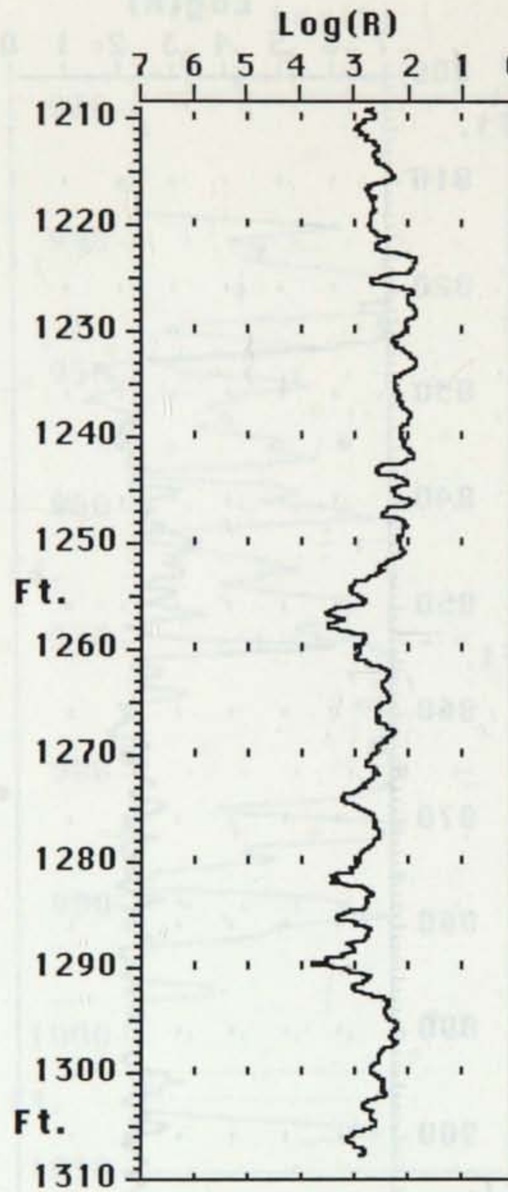
DRILL HOLE: **A–5;** LOCATION: **Aitkin County, 47–26–2–bb**



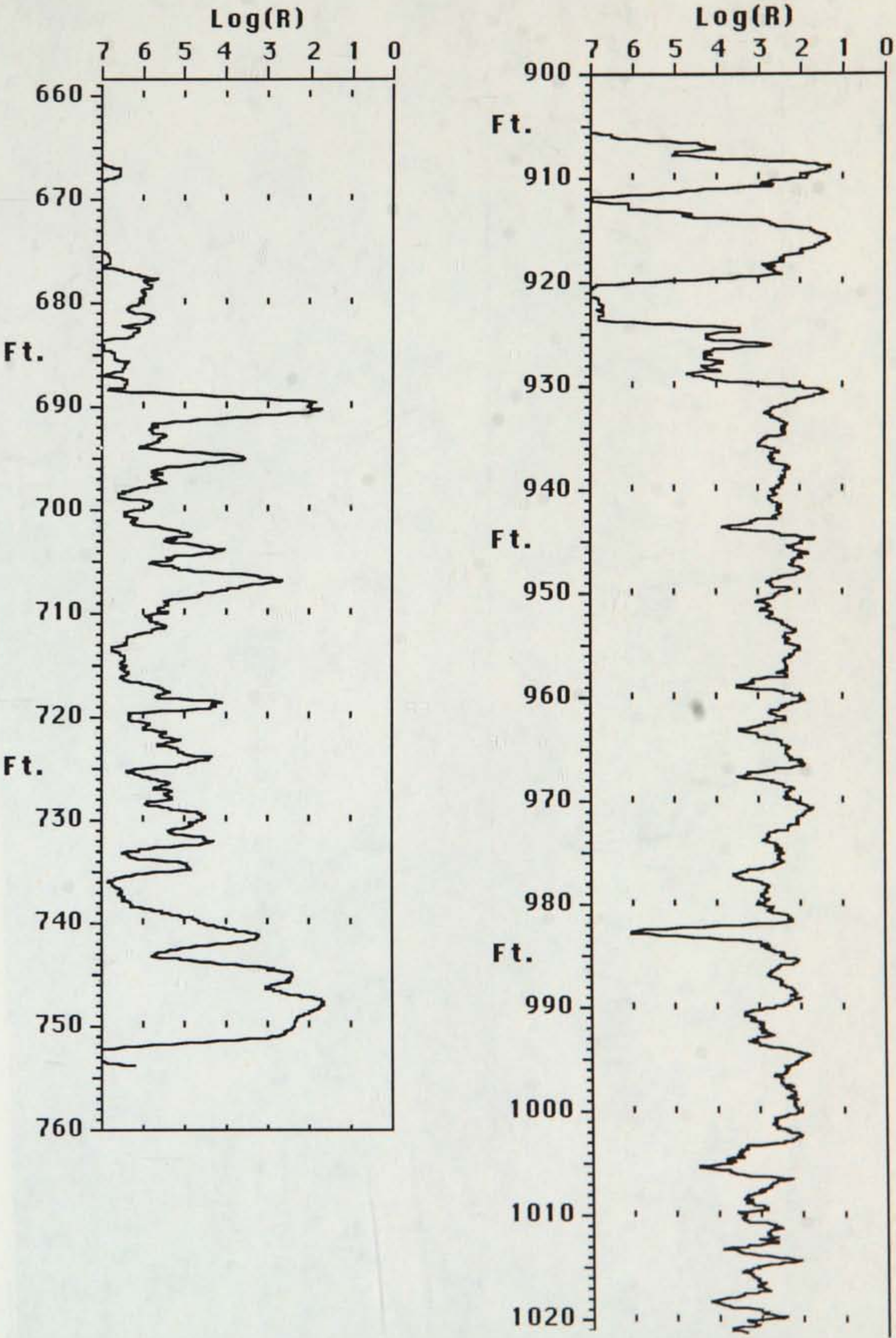


DRILL HOLE A–5 CONTINUED

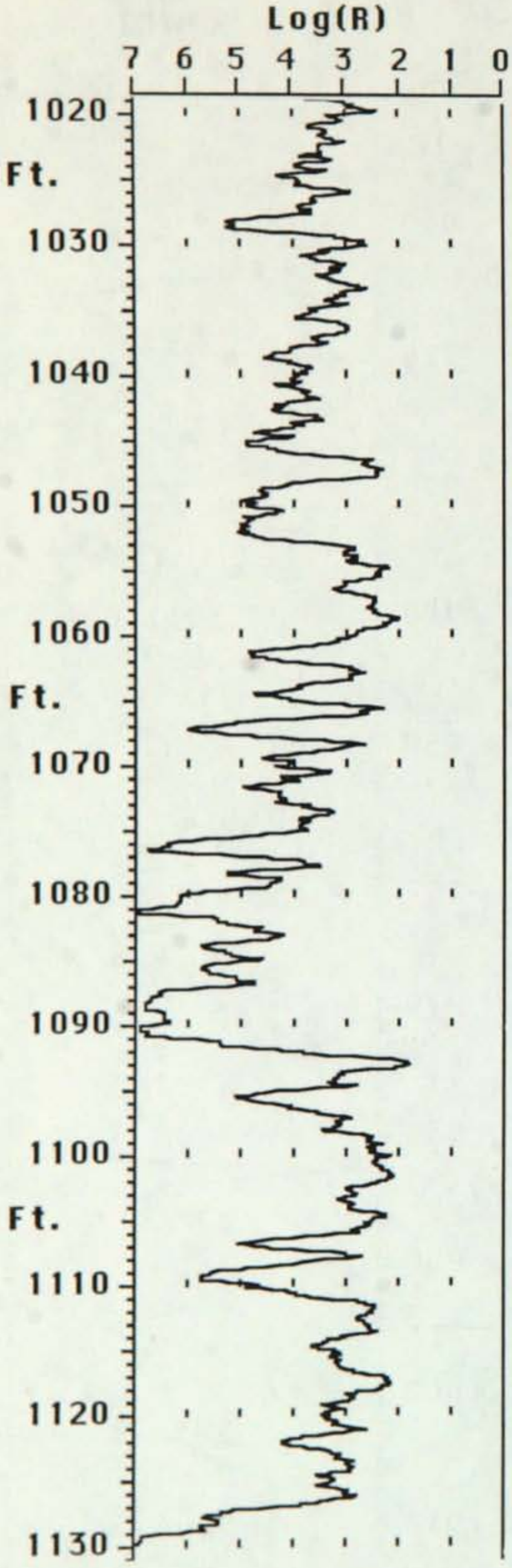




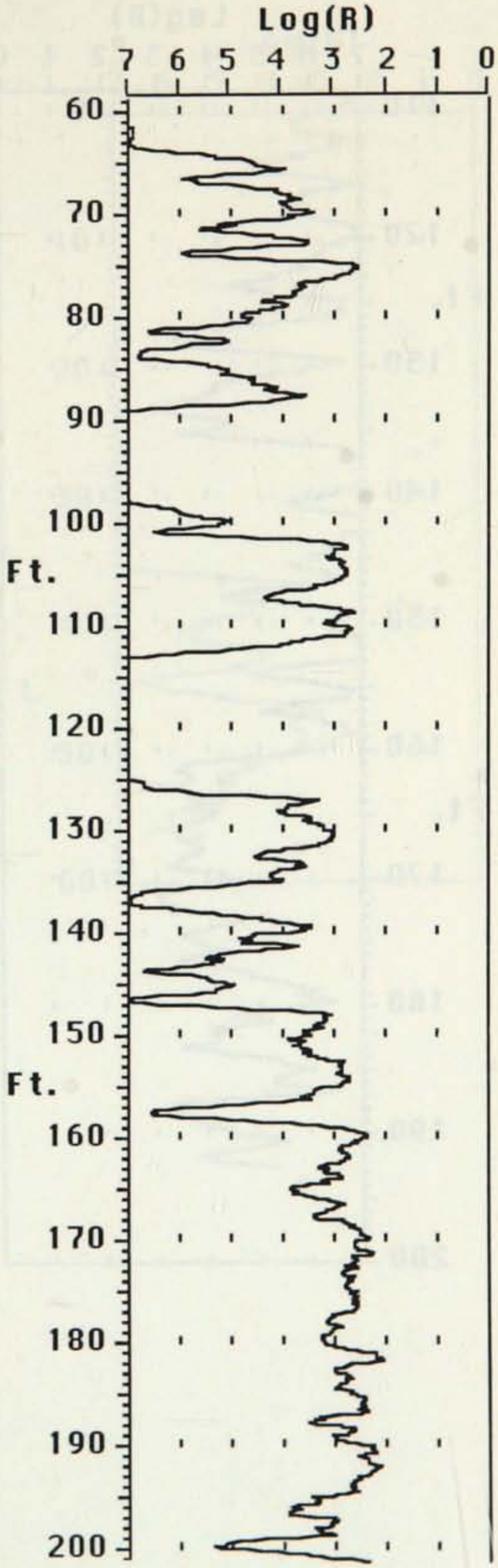
DRILL HOLE: **A–6**; LOCATION: **Aitkin County, 46–25–20–dd**



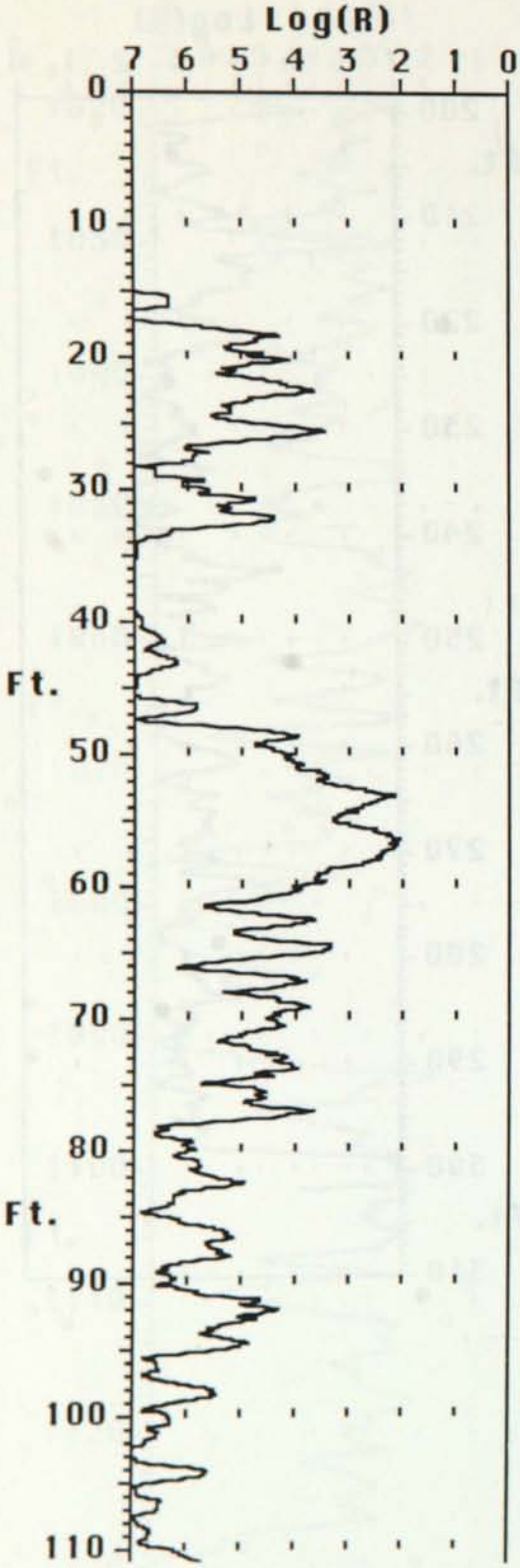
DRILL HOLE A–6 CONTINUED

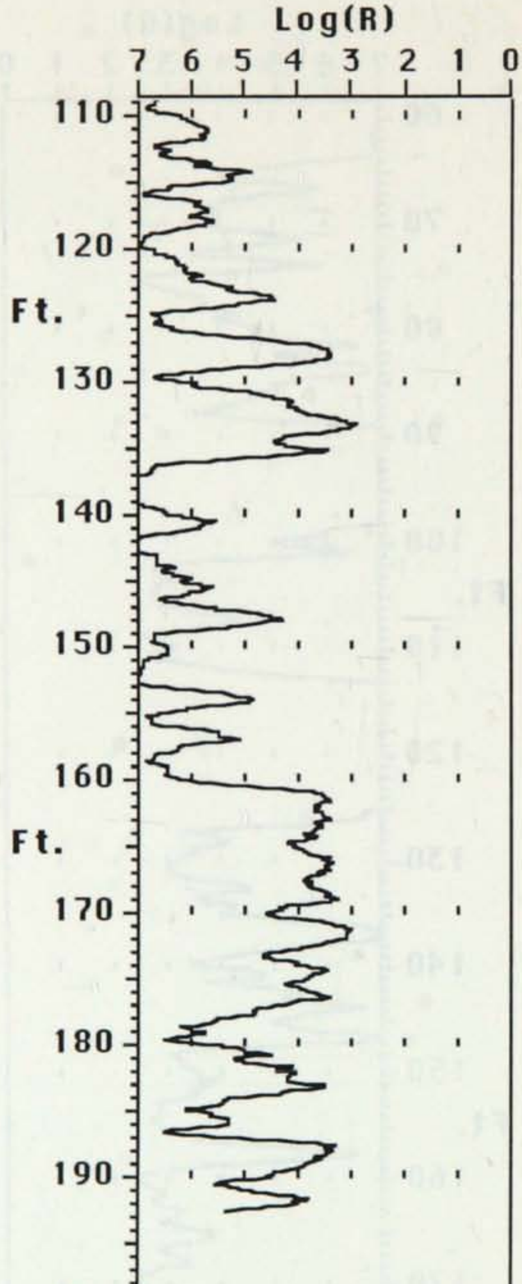


DRILL HOLE: **CL–1**; LOCATION: **Carlton County, 46–20–3–cc**

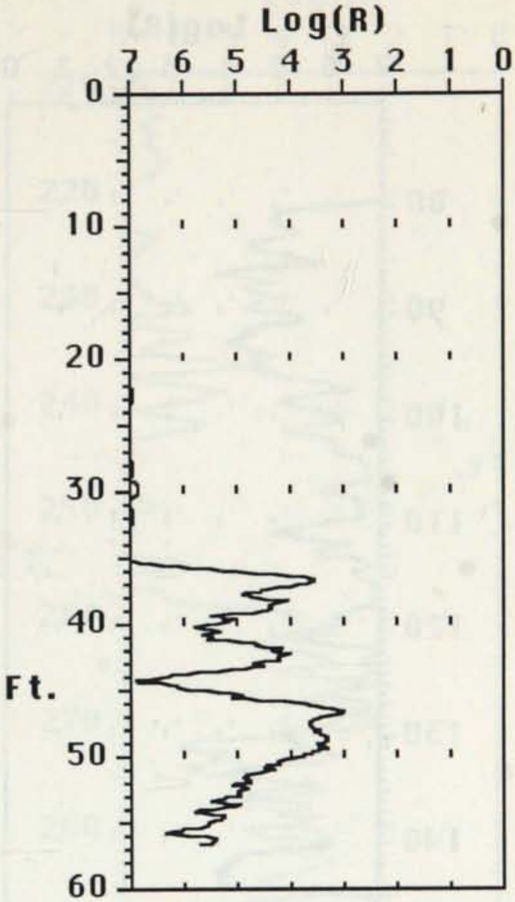


DRILL HOLE: **EL–1**; LOCATION: **Carlton County, 46–20–8–d**

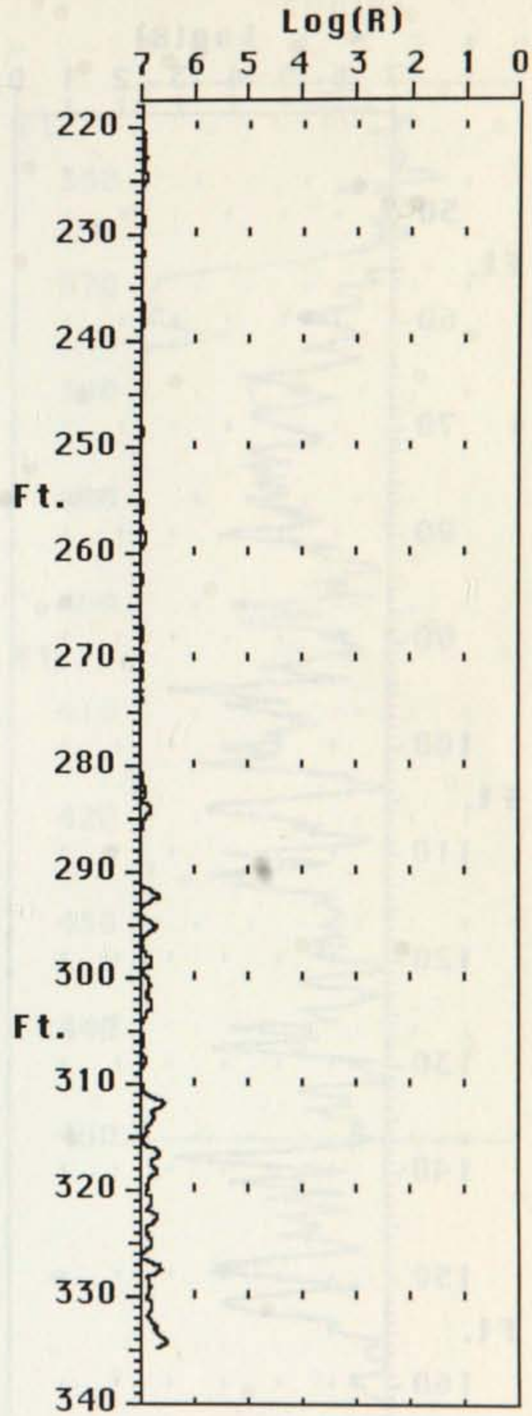




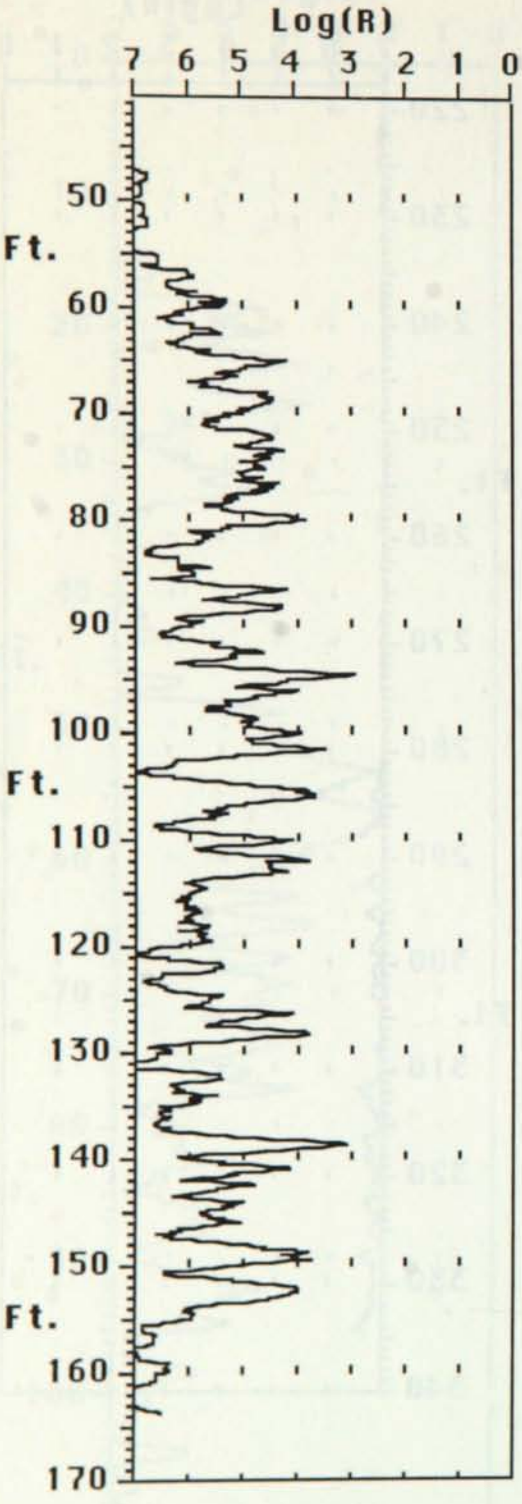
DRILL HOLE: EL–2;
LOCATION: Carlton County, 46–20–8–d



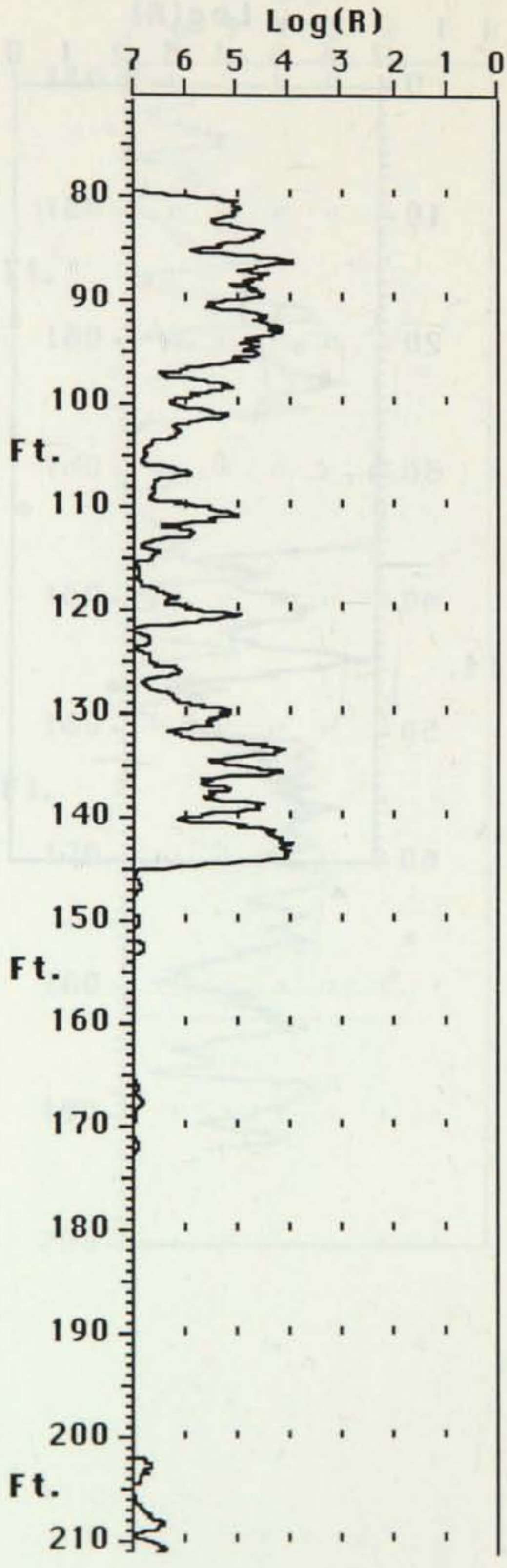
DRILL HOLE: H–1;
LOCATION: Aitkin County, 48–22–30–ca



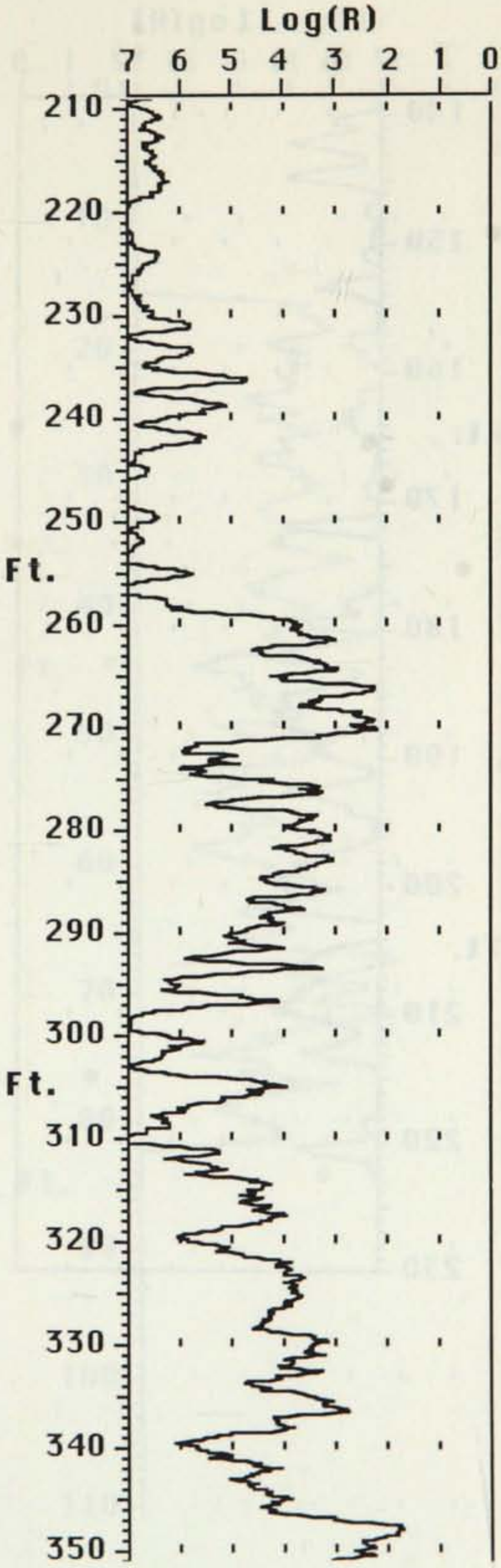
DRILL HOLE: H–G–4;
LOCATION: Aitkin County, 46–25–11–bb

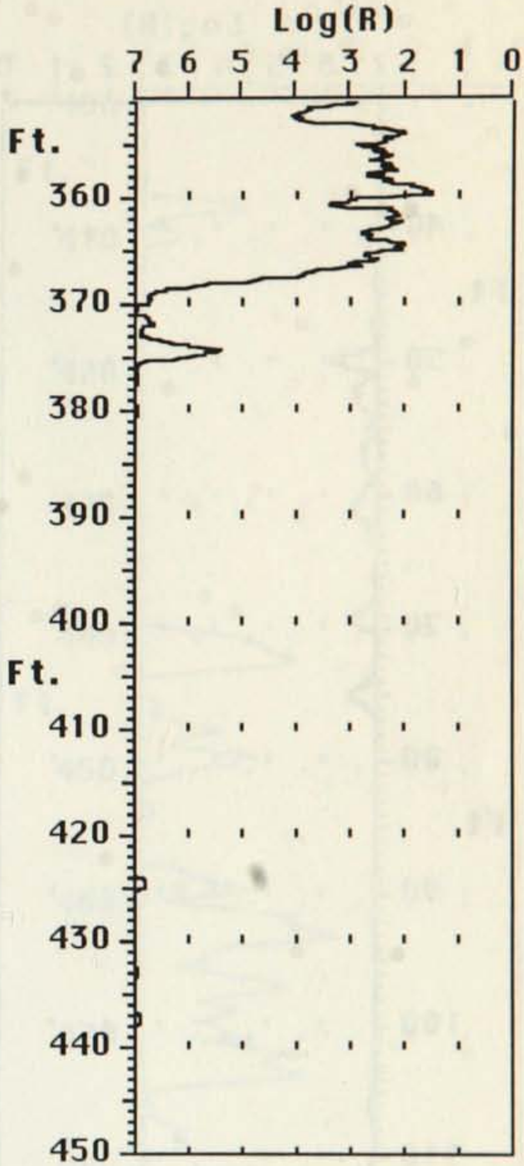


DRILL HOLE: MG–5;
LOCATION: Carlton County, 46–20–7–dc

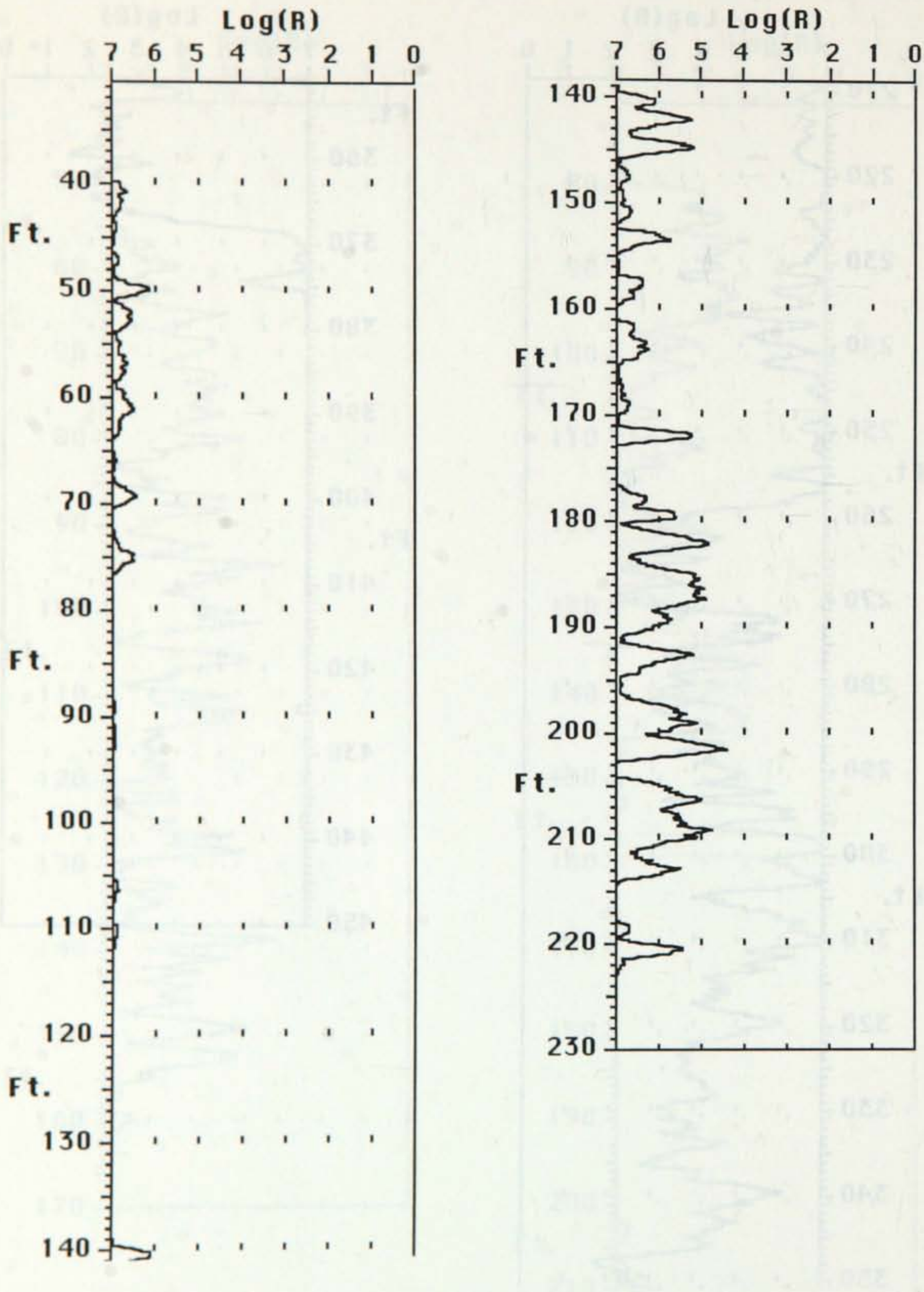


DRILL HOLE MG–5 CONTINUED

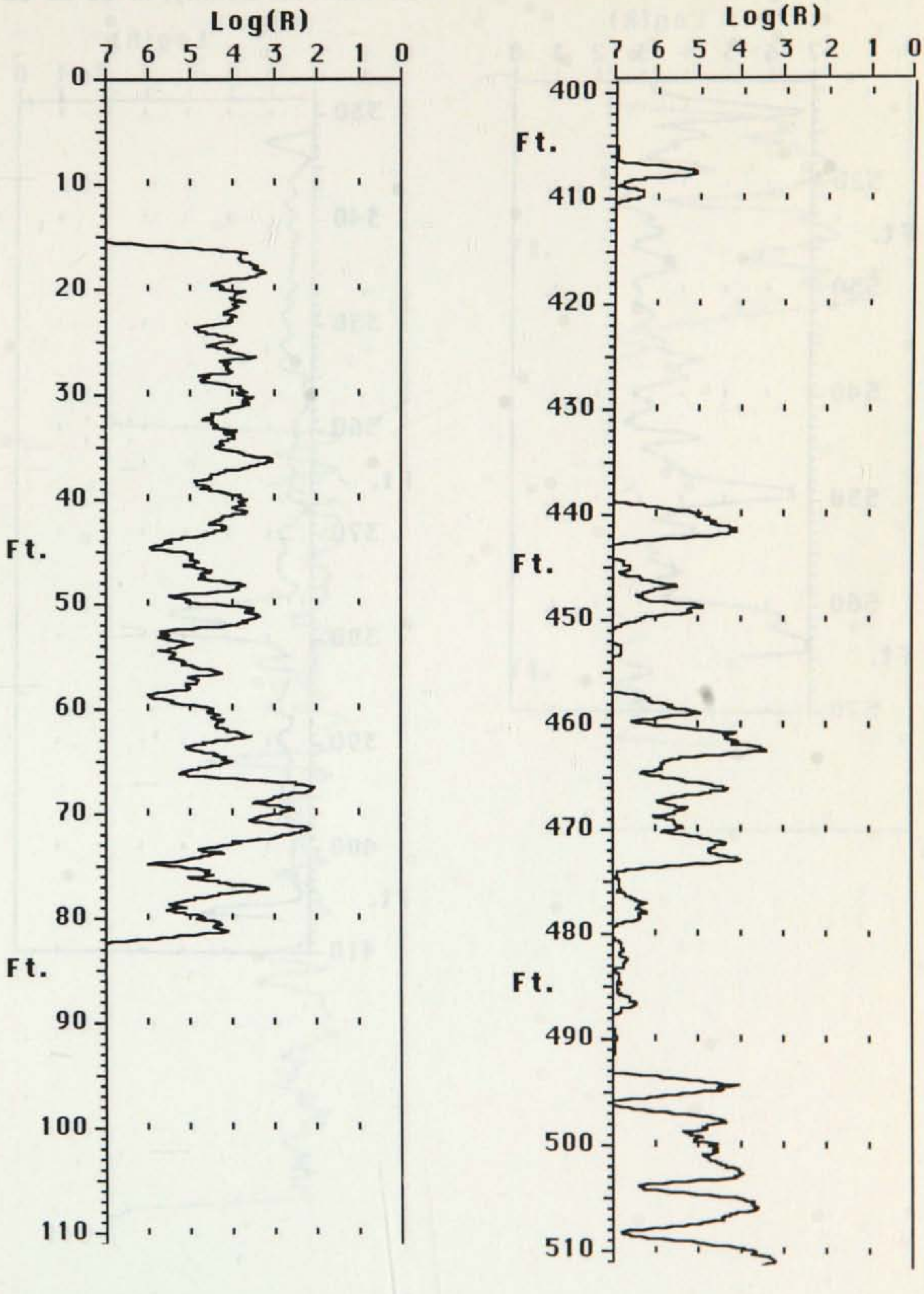




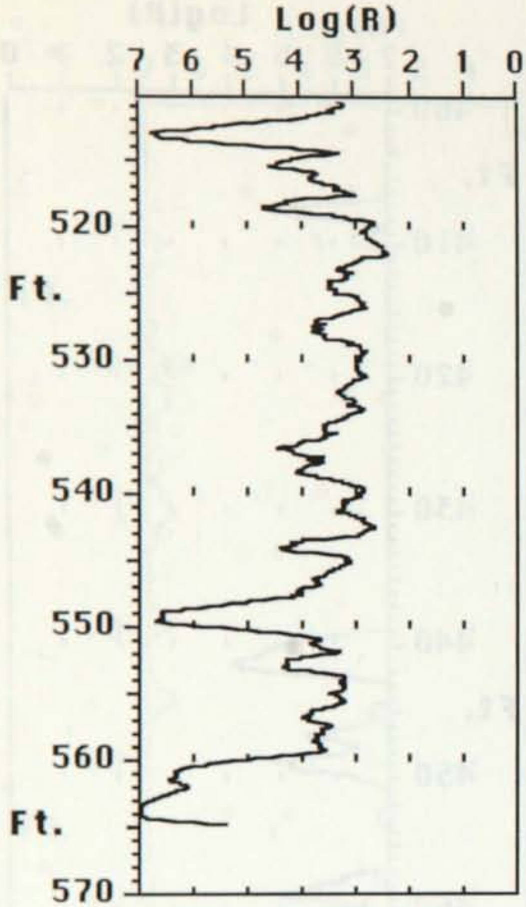
DRILL HOLE: MG–6; LOCATION: Carlton County, 46–20–17–bb



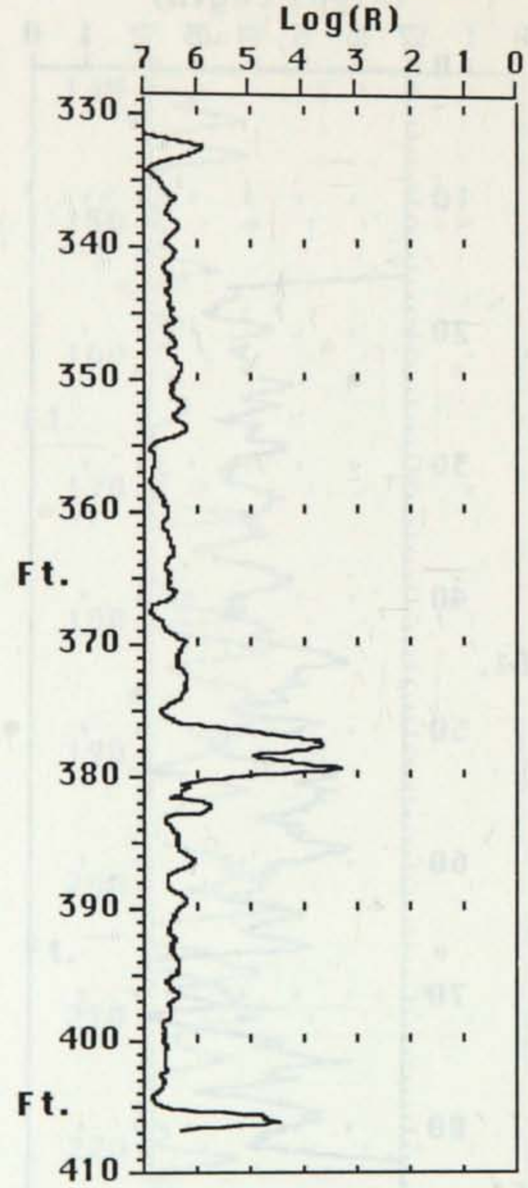
DRILL HOLE: MG–7; LOCATION: Carlton County, 46–20–8–cc



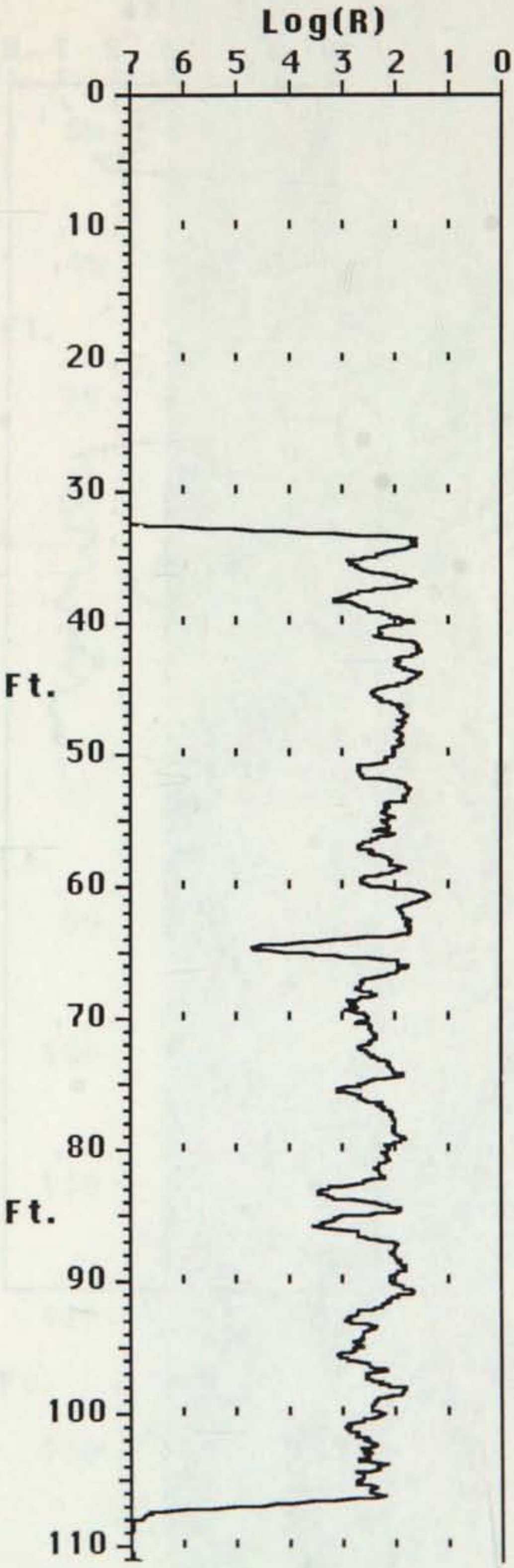
DRILL HOLE MG-7 CONTINUED

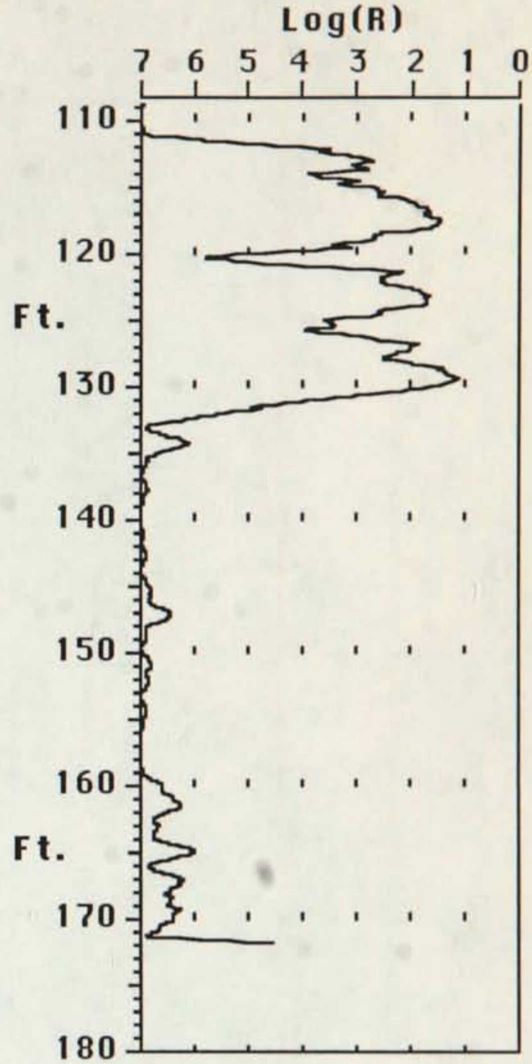


DRILL HOLE: ML-49c;
LOCATION: Pine County, 45-20-29-aa

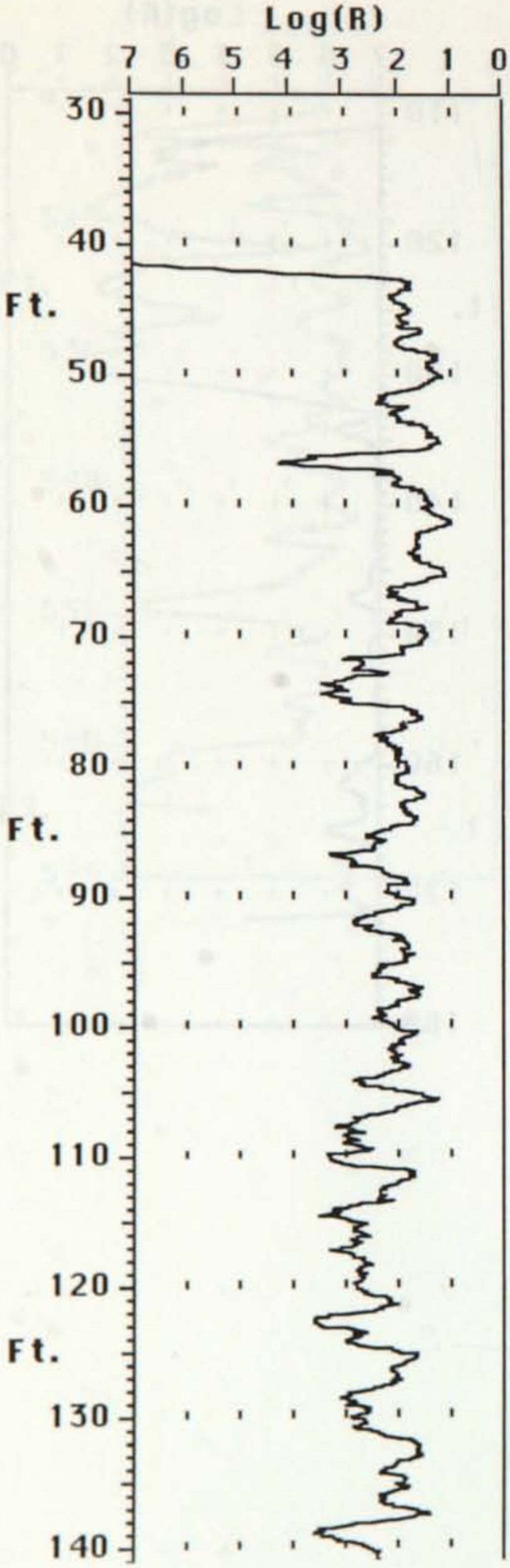


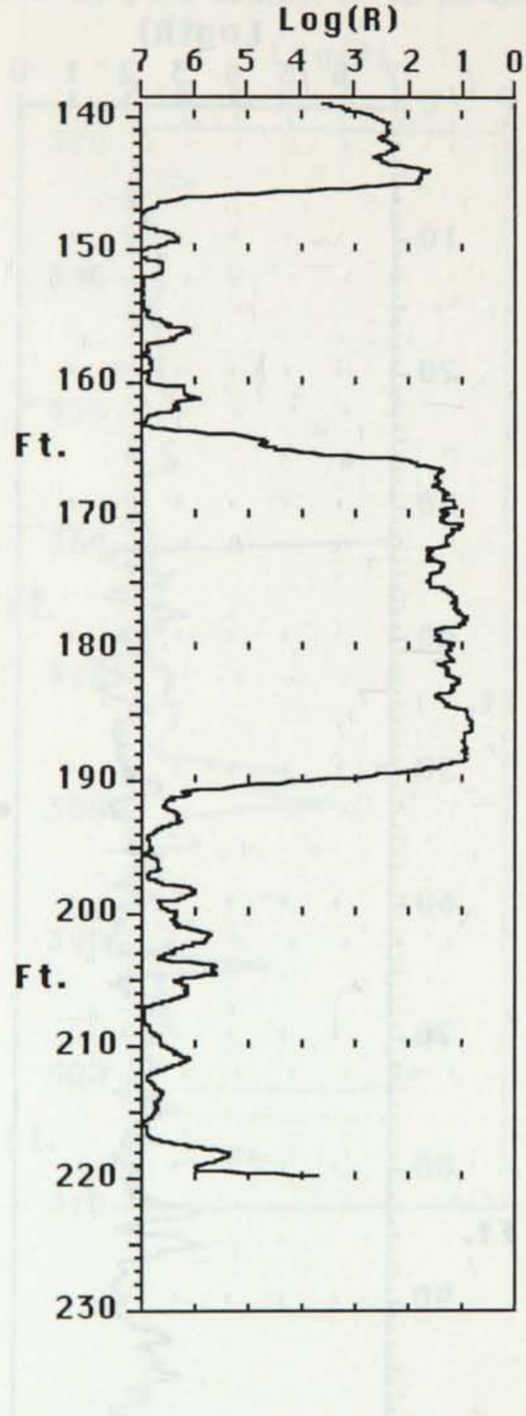
DRILL HOLE: **MLCH-2**; LOCATION: **Carlton County, 48-18-33-bd**



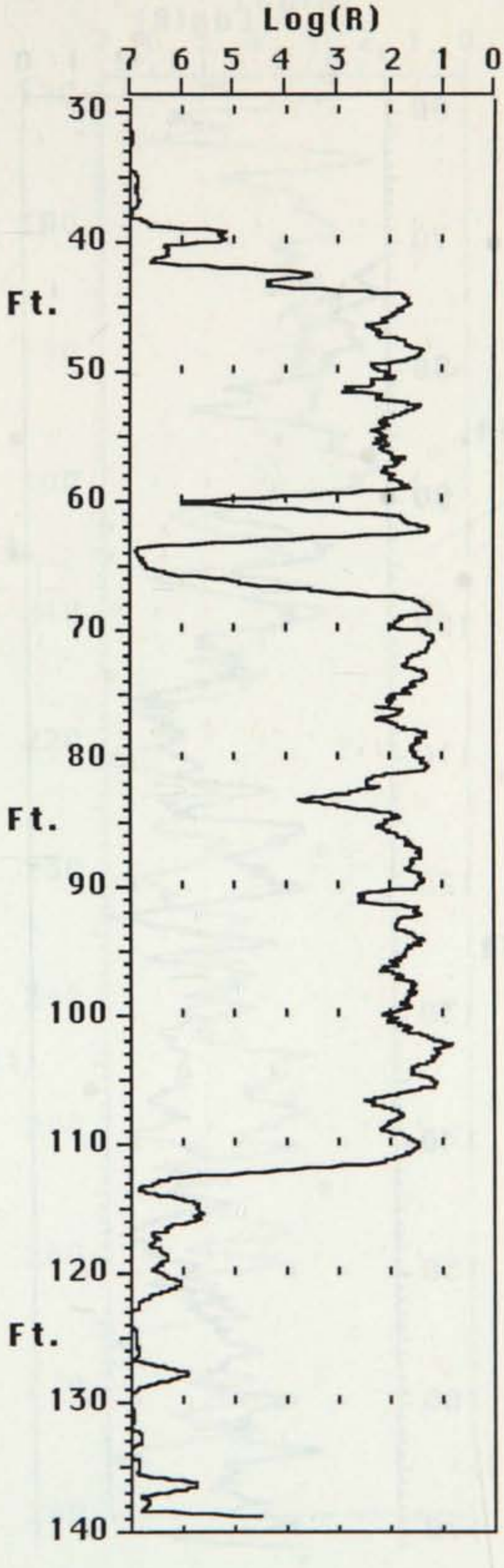


DRILL HOLE: **MLCH-3**; LOCATION: **Carlton County, 48-18-33-bd**

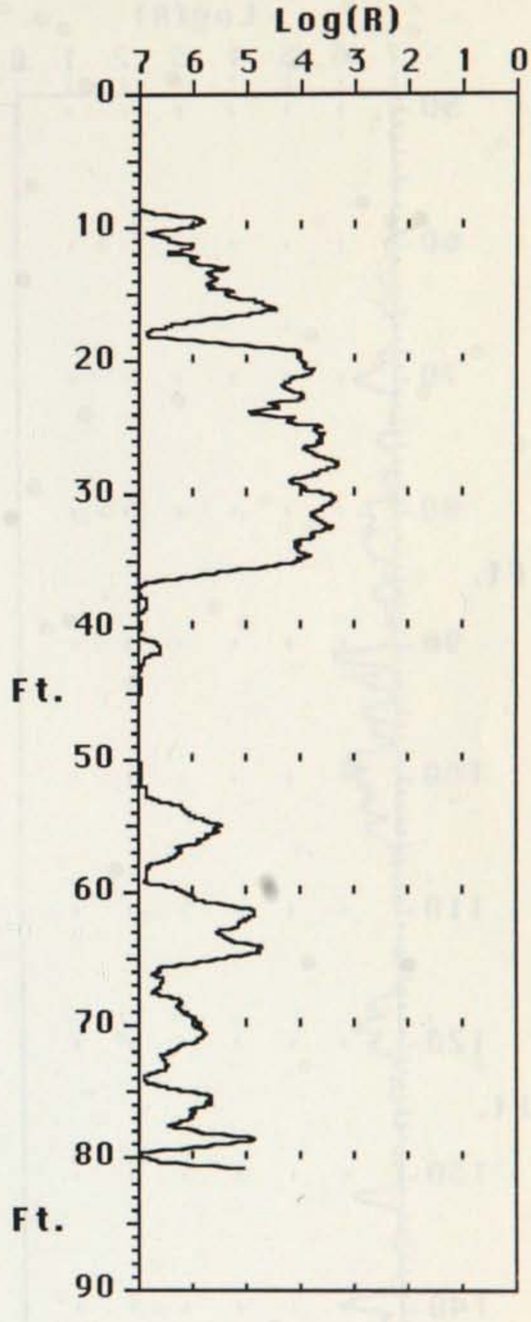




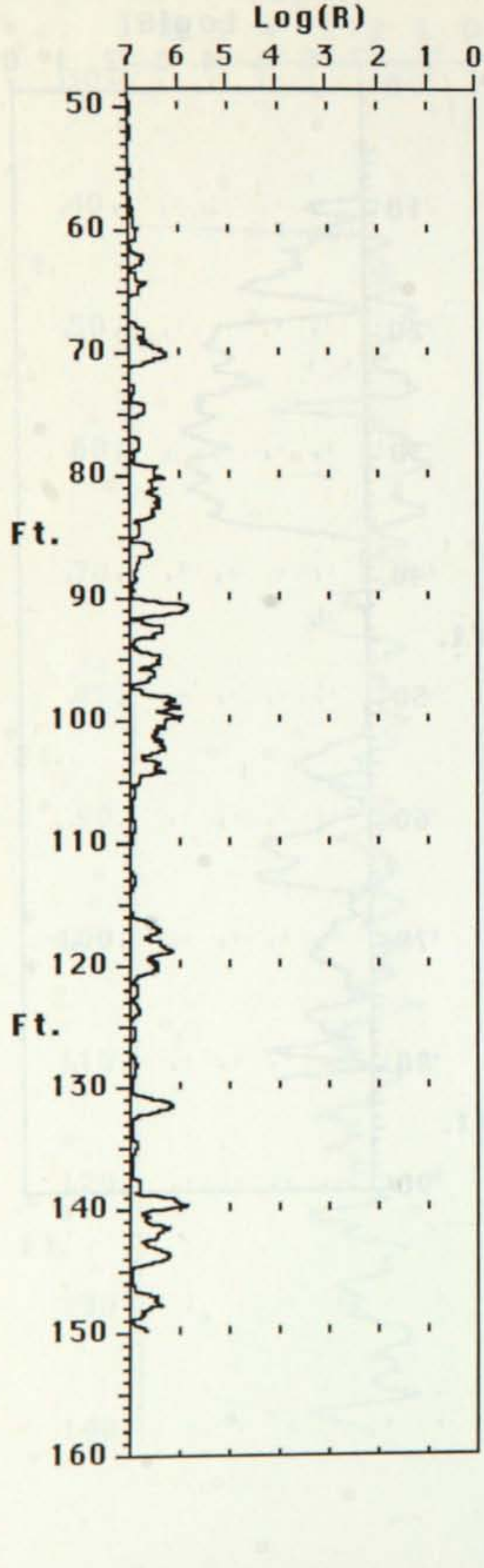
DRILL HOLE: **MLCH-4**;
LOCATION: **Carlton County, 48–18–33–bc**



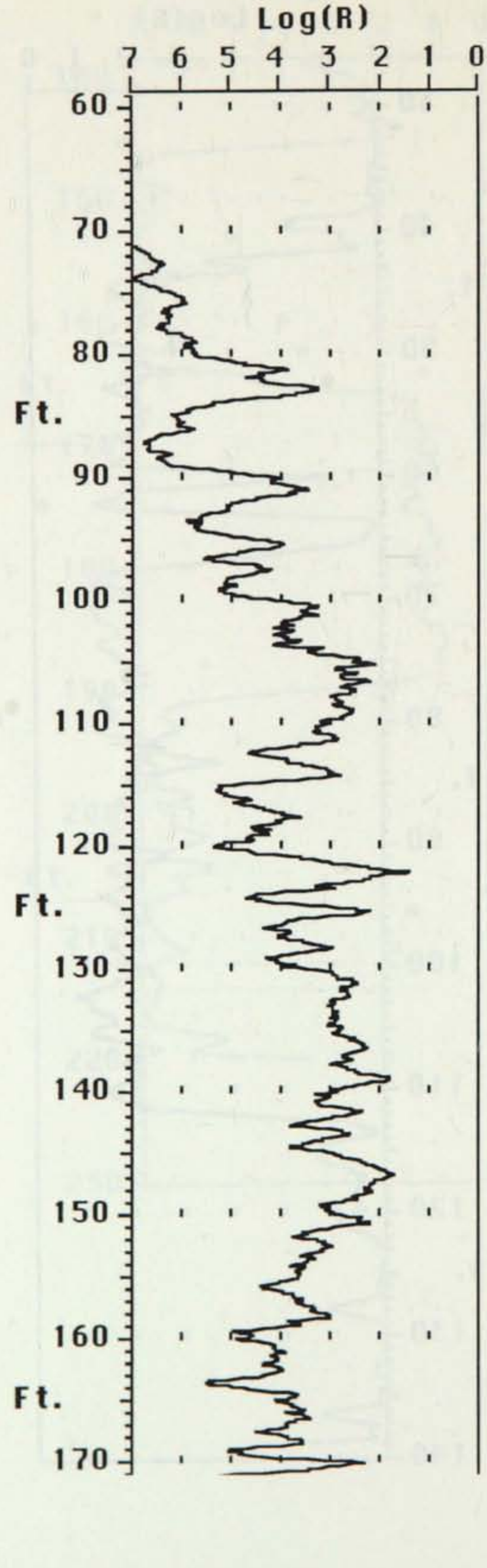
DRILL HOLE: **MLCH-11**;
LOCATION: **Carlton County, 47–18–4–ba**



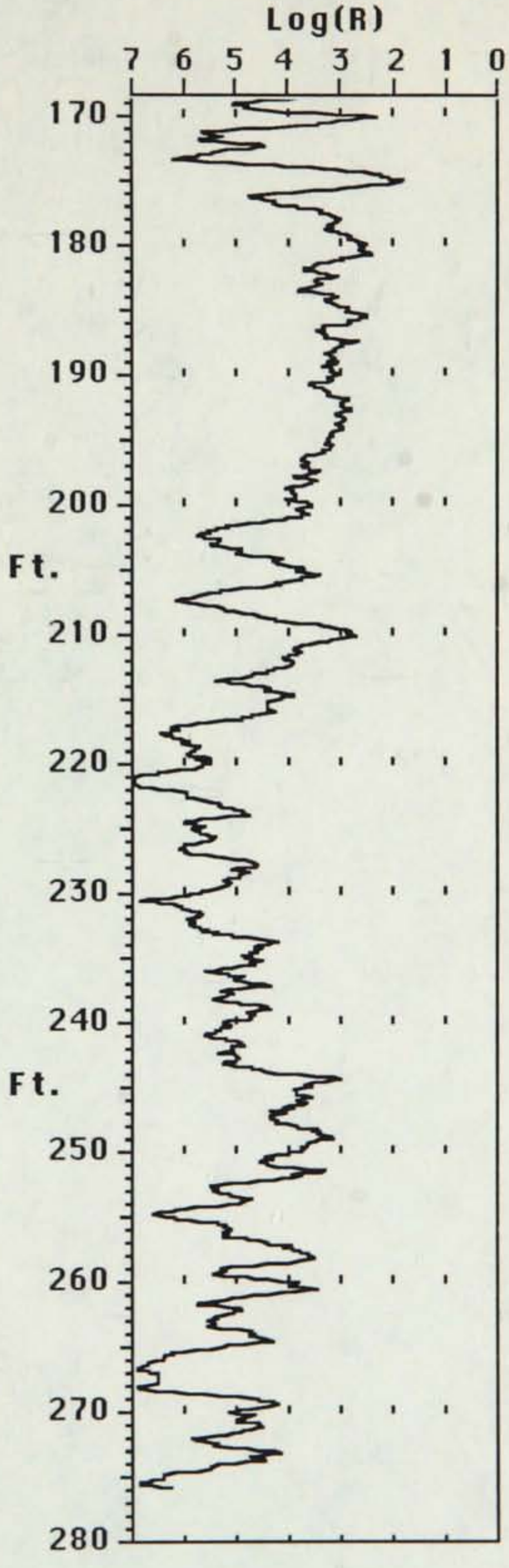
DRILL HOLE: **MM–1**;
LOCATION: **Carlton County, 46–19–7–bb**



DRILL HOLE: **MN–64**;
LOCATION: **Aitkin County, 46–25–28–bd**



DRILL HOLE MN-64 CONTINUED



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

By

Peter L. McSwiggen

ABSTRACT

Resistivity logging is critical in evaluating carbon-rich drill core, because visual methods have proven to be very inaccurate. A hand-held device for logging resistivity in drill core, called CoReLog, was developed at the Minnesota Geological Survey. Continuous resistivity logs produced by the device have been very effective in determining the distribution of carbonaceous units and accurately estimating the carbon content of drill core.

INTRODUCTION

Any investigation of carbonaceous rocks for either a paragenetic or economic objective requires a knowledge of the abundance of carbon and how it is distributed, both geographically and stratigraphically. The general geographic distribution of carbonaceous rocks can be delineated using a number of surface or airborne electrical geophysical techniques (Keller and Frischknecht, 1966; Telford and others, 1976). Detailed work, however, requires core drilling and direct evaluation of the rock itself. Visual logging of core can supply a wealth of information, but it is difficult to nearly impossible to accurately estimate the carbon content of any particular sample or interval. Both the color and degree to which a sample discolors the observer's hands are poor indicators of the abundance of carbon. Because of the highly conductive nature of carbonaceous material, the measured resistivity of a sample can be an accurate indicator of carbon content in most circumstances.

Almost any resistivity meter allows for detailed single point measurements. If the objective, though, is to make continuous strip log charts along lengths of core, then using such a meter is extremely time consuming and therefore ineffective for acquiring detailed results. What is needed is a device that can be moved along the core and have the resistivity values feed automatically into a computer. Such a device and associated system was developed as part of a graphite research program at the Minnesota Geological Survey, and it is currently being investigated in regard to its patentability.

CoReLog is a hand-held core resistivity logging device that feeds directly to a microcomputer for making continuous resistivity logs of carbon-bearing drill core. As the device is being rolled along the core, the microcomputer monitors the distance traveled and makes resistivity measurements at a predetermined interval. The data are then stored on floppy disks for later use.

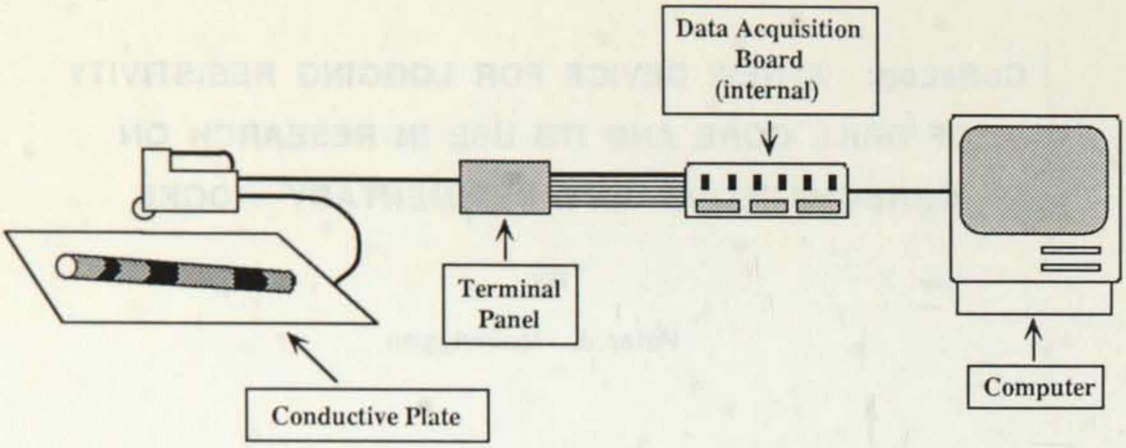


Figure 5. CoReLog system configuration.

Computer software developed as part of this system produces strip logs from these data at a scale determined by the user. Having the data in a digital form also allows the user the option of performing any required statistical analyses of these data.

DESCRIPTION OF THE CoReLog SYSTEM

CoReLog is a hand-held electrical-mechanical device that is interfaced to a microcomputer through a data acquisition board (Fig. 5). The CoReLog device consists of two tracking wheels that can be rolled along the core (Fig. 6). These two conductive wheels can be used as the bridge across which the resistance is measured. Mounted between the wheels is a gear, and plastic spacers are used to electrically separate the wheels from each other and the gear. These parts are attached together as a single assembly in order that they roll together as a unit. The assembly then rides on a nonconductive plastic rod. Outside of both wheels rest ultra-thin metal sheets, which are not attached to the assembly but are in contact with it. This allows the wheels to roll freely, yet be in electrical contact with the system.

As the assembly is rolled along the core, the inner gear drives an offset gear, which in turn drives an optical switch-timing assembly. The optical switch is monitored by the computer to determine the distance traveled by the CoReLog device. To reduce the possibility of collecting spurious data by mistake, the optical switch has a current flowing to it only when the button on top of the device is depressed.

There are two modes under which CoReLog can operate. In one mode, the two wheels act as the bridge across which the resistance is measured. In the second mode, a plug is inserted into a three-conductor jack in the back of the device. The plug disconnects the circuit to one of the wheels and allows for an external second contact. What is usually used for this external contact is a conductive plate on which the core can lie. Each mode has its advantages and disadvantages, as will be discussed later.

The CoReLog device is connected to a data acquisition board through a terminal panel. Two of the channels on the acquisition board are used to collect data. A digital channel is used for monitoring the optical switch, and an analog channel is used for measuring the voltage drop between the two contacts. The system was built around an acquisition board (ACSE-12-8) from Strawberry Tree Computers (Note: Use of trade and company names in this report is for descriptive

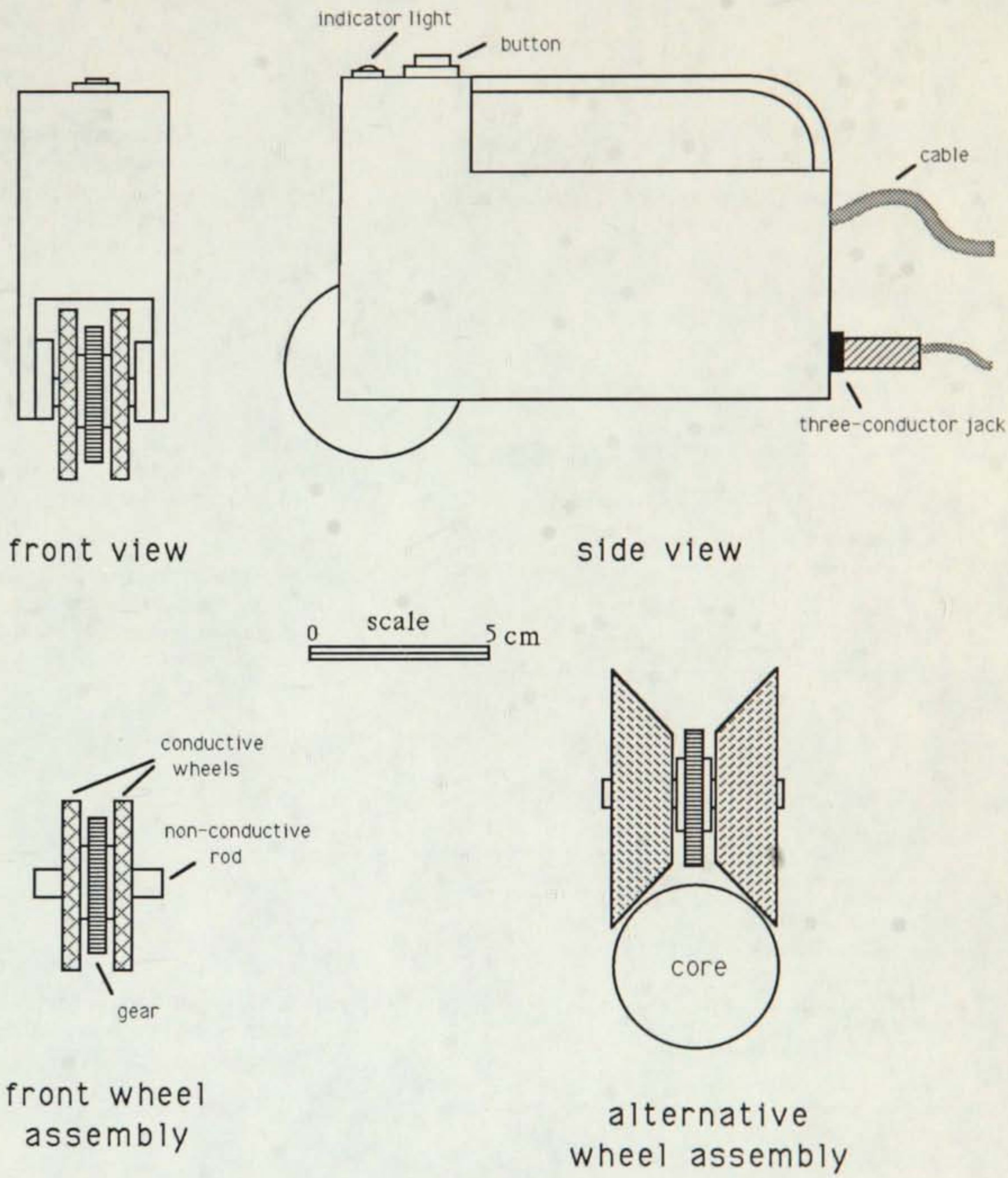


Figure 6. CoReLog device.

purposes only and does not constitute endorsement by the Minnesota Geological Survey or the University of Minnesota).

The driving force behind the system is the computer software. It currently consists of two parts: RLogger is the data collection software, and PlotLog is the software for viewing and printing the data as strip logs. RLogger has two modes: an analog mode and a digital mode. When RLogger is in its analog mode it operates like a normal resistivity meter. The resistivity of the sample is

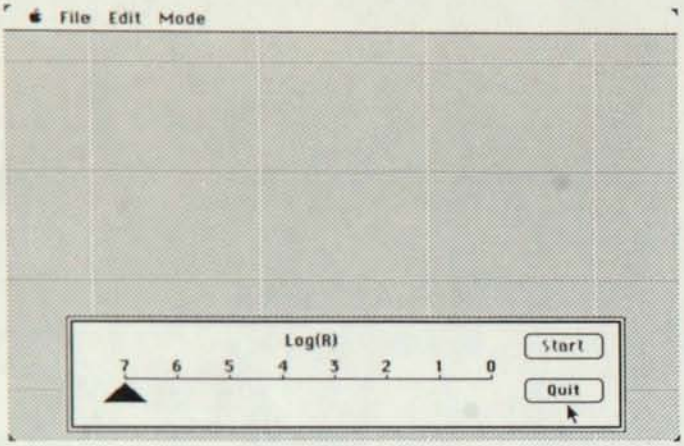


Figure 7. Program RLogger in its analog mode. In this mode the device operates like a normal resistivity meter. Values are output on a scale showing the logarithm of the measurements.

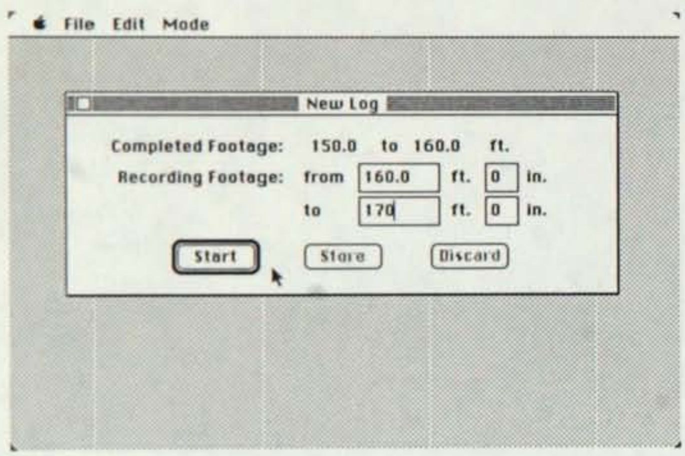


Figure 8. Program RLogger in its digital input mode, showing the completed footage and footage for the interval being recorded.

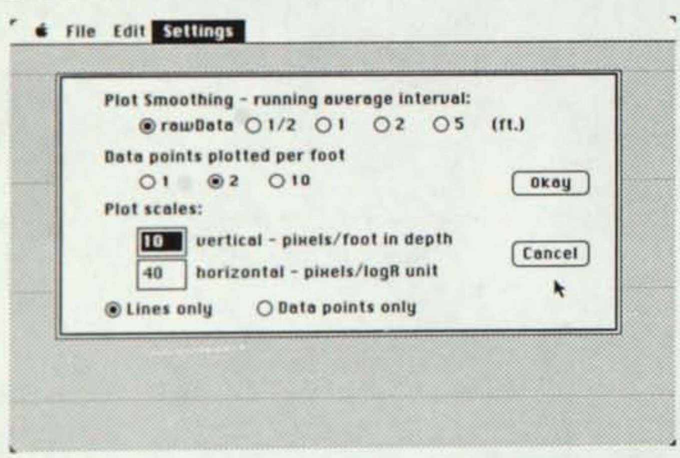


Figure 9. Optional settings for plotting data from the program PlotLog.

measured in ohms and the logarithm of this value is output on a scale from 0 to 7 on the computer screen (Fig. 7), where 7 corresponds to 10 megohms and 0 corresponds to 1 ohm. In this mode the data are not stored, but are only shown on the screen. This mode is most useful for determining the general variations in resistivity of a core or for looking for a specific conductive zone.

In the digital mode the data are not displayed on the screen, but are recorded directly on a floppy disk. A window is displayed on the screen which tells the user the beginning and ending footage of the core already logged, and allows the user to input the footage of the next interval to

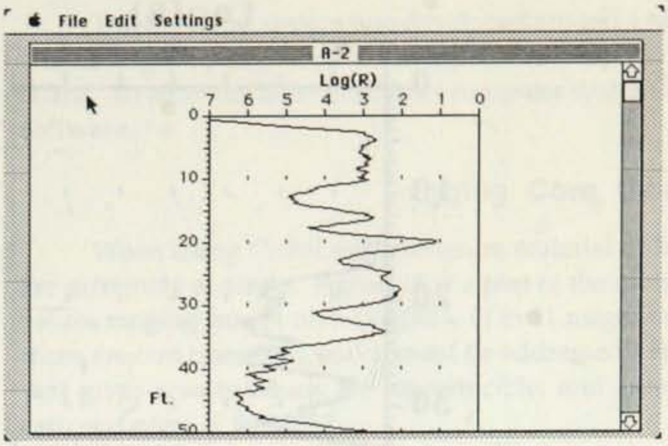


Figure 10. An example of a resistivity plot using the program PlotLog (plotted using a 2-foot running average)

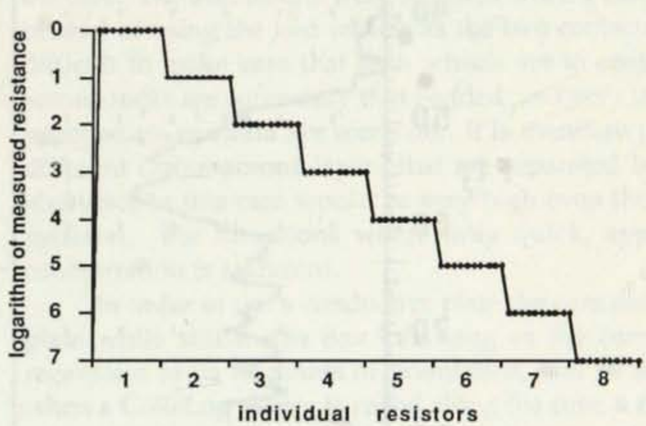


Figure 11. Measured values of a set of resistors: 1 = 1 ohm; 2 = 10 ohms; 3 = 100 ohms; 4 = 1 kilohm; 5 = 11 kilohms; 6 = 100 kilohms; 7 = 1 megohm; 8 = 11 megohms.

be logged (Fig. 8). The input footage should be points where the true depth of the core is known. Often some sections of core are not recovered during drilling. If the interval is large enough, it can be skipped; the program will record a value greater than 7, and the interval can later be easily identified as a zone of missing core. Commonly it is not known where the core is missing, although the length of core is shorter than the interval indicates. In these situations the program scales the recorded data so that it is equally spaced over the entire interval. In CoReLog's present configuration it records measurements at a rate of approximately one reading per 0.1 inch. The program RLogger collects these data, scales them and then averages every 10 values so that the spacing between each stored data point is equal to 0.1 foot.

After each run the user has the option of either storing the data or discarding it if the data were collected badly or mistakes made. If the data are discarded, the interval can be rerun. Otherwise the completed footages are updated by the computer and a new cycle is ready to begin.

Once the data have been collected the results can be viewed or printed with PlotLog. As shown in Figure 9, the user has a number of options. The data can be smoothed by using one of a number of running average intervals, or the data within a given footage can be averaged to a single value. The scale of the plot is user defined, as is whether the data will be plotted as points or as continuous lines (Fig. 10). If the data are plotted on a dot matrix printer, a continuous strip log is generated. If the output is from a laser printer, finer detail is possible but the log is broken into 8.5" x 11" segments.

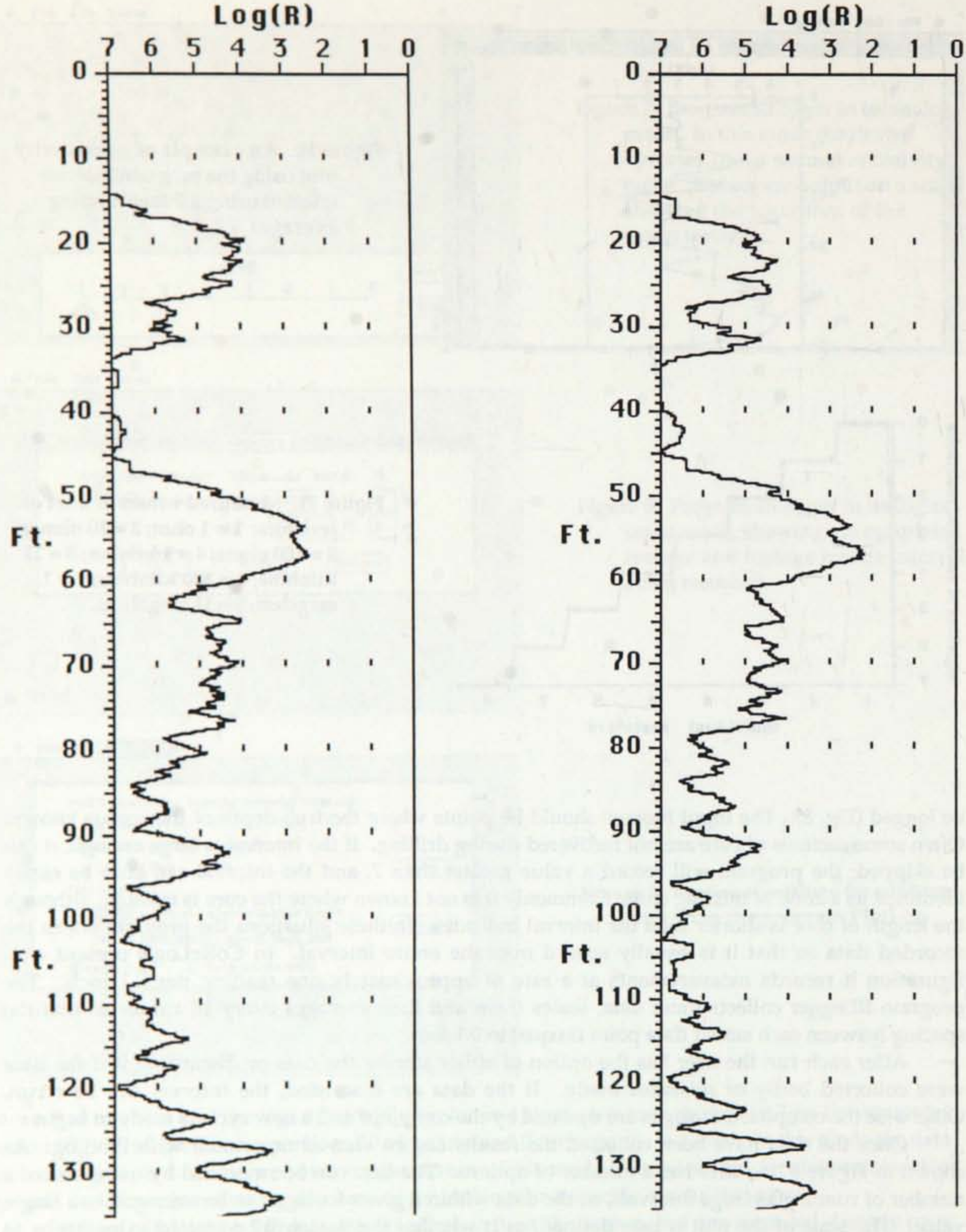


Figure 12. A comparison of two logs of the same core measured at two different times (plotted using a 2-foot running average. Some variations occur, but in general there is good agreement between the two logs.

The CoReLog system was developed around a Macintosh SE computer, but the CoReLog device would work equally well with any microcomputer that is capable of taking a data acquisition board. To accommodate a different computer system would only require a rewriting of the computer software.

Logging Core Using CoReLog

When using CoReLog to measure material of known resistance, such as resistors, the results are extremely accurate. Figure 11 is a plot of the measured values from a series of resistors that had values ranging from 1 ohm (log(R) = 0) to 11 megohms (log(R) = 7.04). When measuring actual core there are two questions which must be addressed. First, can core be logged in a consistent manner that gives results which are reproducible; and second, can the system be calibrated to give the carbon content of the core?

How consistent the results are depends largely on how much care was taken during logging of the core. The best results were obtained when a conductive plate was used as one side of the bridge, instead of using the two wheels as the two contacts. There are two main reasons. First, it is very difficult to make sure that both wheels are in continuous contact with the core. Second, carbonaceous rocks are commonly thin bedded, and very thin layers of carbonaceous material separated by nonconductive strata are common. It is therefore possible to have the two wheels in contact with different carbonaceous layers that are separated by an insulating siliceous layer. The measured resistance in this case would be very high even though both contacts were touching carbonaceous material. For situations where only quick, approximate results are desired, the two-wheel configuration is sufficient.

In order to use a conductive plate the core can be removed from the core box or placed on the plate while still in the box. As long as the core lies flat on the conductive plate, each layer, regardless of its thickness or orientation, will be in contact with the underlying plate. Therefore when a CoReLog device is rolled along the core, a current is generated at each conductive layer. In practice it was found that this approach is very fast even when care is taken and the results are reproducible. Figure 12 shows two logs recorded for the same core at different times. Though some of the small details may vary, it can be seen that the method gives consistent results overall. A more quantitative comparison of the results is shown in Figure 13. The results again indicate that on a small scale there are differences, but on a large scale the values are quite consistent.

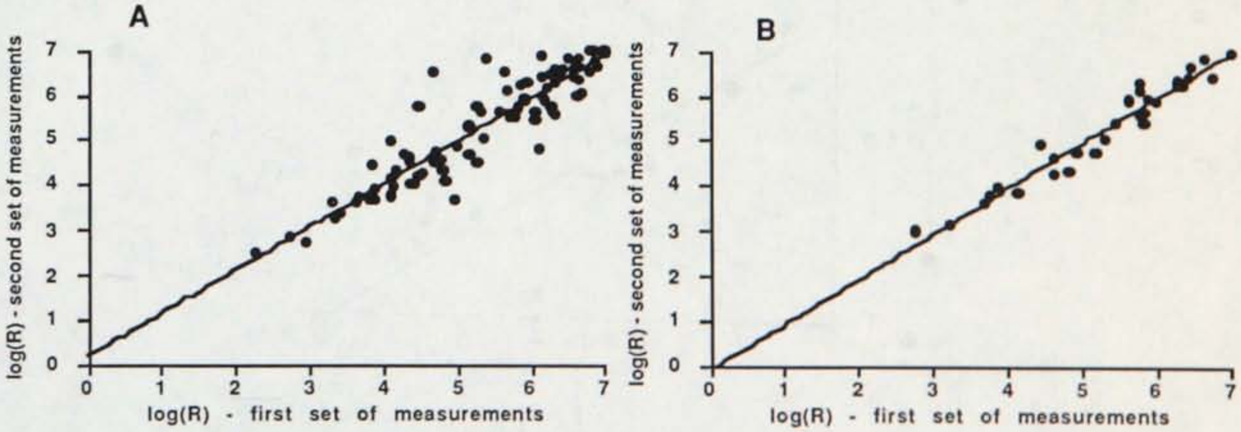


Figure 13. The values from each depth interval from the two plots in Figure 12 are plotted against each other to obtain a quantitative comparison of the data. A, data averaged over a 2-foot interval; B, data averaged over a 5-foot interval.

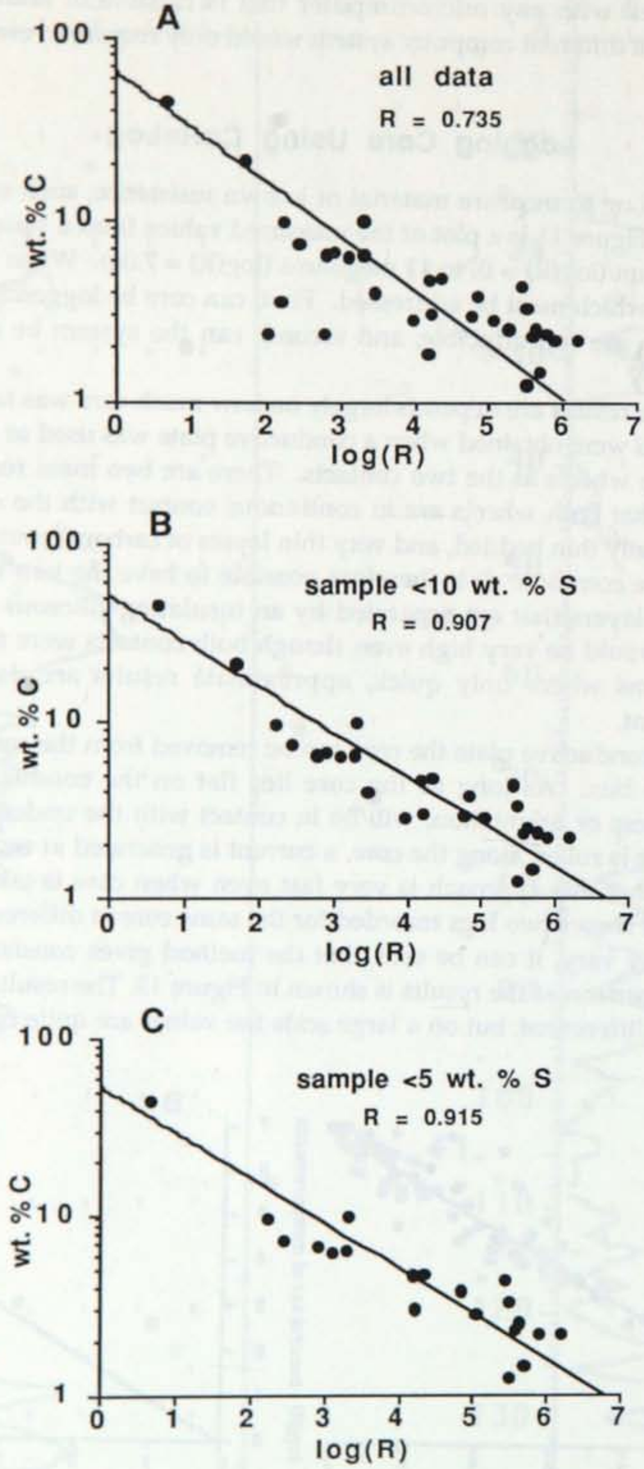


Figure 14. Correlation of the measured resistance relative to the abundance of carbon.

Also important is whether this method can estimate the actual carbon content of a sample or a stratigraphic interval. Factors that may affect the resistivity of a rock include the abundance of carbonaceous material, the crystallinity of the carbonaceous material, and the presence of other conducting minerals such as iron sulfides. Graphite has the ability to conduct electric currents through a rock even when it occurs in small amounts, such as 1-2 wt.% of the rock. The percentage of sulfide minerals required in a rock to conduct a current appears to be much higher, presumably because of the difference in crystal shape and textural arrangement of sulfide minerals. Graphite occurs as a platy mineral, typically intergrown, with a preferred orientation parallel to the foliation of the rock. Sulfide minerals, in particular pyrite and pyrrhotite, typically form equant-shaped grains, which occur in interlocking bands only if they make up a large percentage of the rock. When sulfide minerals and graphite both occur in the rock, the conductivity is largely controlled by the abundance of graphite (Fig. 14). This is the case until the sulfide minerals make up more than 20 percent of the rock (>10 wt.% S).

Figure 14a is a plot of the carbon content relative to the measured resistance for all samples collected, which includes samples containing as much as 26 wt.% sulfur (approximately 50 wt.% pyrite). The resulting plot shows a significant scatter away from the calculated least-square-fit regression line. If only those samples with less then 10 wt.% S are plotted (Fig. 14b), the amount of scatter is greatly reduced, and the data approximate a linear relationship much more closely. If only those samples with less than 5 wt.% S are plotted (Fig. 14c), there is no significant improvement from the preceding plot.

This suggests that when the sulfide content of the rock is greater than 20 wt.% (>10 wt.% S), the minerals begin to develop an interlocking network of grains that allows the current to flow independent of the graphite. Below this amount the sulfide minerals occur as isolated grains and therefore are not conductive across the sample without the presence of graphite. This makes the abundance of graphite the controlling factor.

Preliminary results therefore suggest that for most carbonaceous rocks that do not contain more than 10 wt.% sulfur, as sulfide minerals, the abundance of carbon can be adequately estimated by the function:

$$\log (C) = 1.726 - 0.245 \log(R),$$

where R is in ohms and C is in weight percent.

Other minerals besides sulfides and graphite can increase the conductivity of a sample without occurring in great abundance, if they occur in the right form. Hematite exsolved from ankerite, for example, greatly increases the conductivity, because it forms as a ubiquitous thin film between grain boundaries, which creates numerous paths for the electrical current to follow.

Data are currently insufficient to determine the extent to which the crystallinity of the carbonaceous material affects the conductivity of the sample.

CONCLUSIONS

A new hand-held resistivity logging device called CoReLog, developed at the Minnesota Geological Survey, has been very effective in characterizing the distribution and abundance of carbonaceous material in drill core. The device is connected to a microcomputer through a data acquisition board allowing data to be collected quickly and continuously. Software developed as part of this system is able to generate continuous strip charts of these data at a scale determined by the user and with various curve-smoothing options.

ACKNOWLEDGMENTS

This project was in part supported by the basic research component of the Minerals Diversification Program as administered by the Minerals Coordinating Committee for the Minnesota State Legislature. This project has also benefited from the electrical assistance given by John P. McSwiggen.

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