TEXT TO ACCOMPANY
BOUGUER ANOMALY GRAVITY MAP OF WISCONSIN

by

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and

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University of Wisconsin - Extension

GEOLOGICAL AND NATURAL HISTORY SURVEY

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1974

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Introduction

The Bouguer anomaly gravity map of Wisconsin is a by-product of a program begun in 1969 at the University of Wisconsin, Madison to compile a comprehensive list of all Wisconsin geophysical data in the public domain. This list was to aid in determining those areas where additional effort would prove most useful. The compilation revealed that the most complete published gravity map (Woollard, 1964) did not include all of the public data and that a substantial amount of new data would soon be available.

Therefore, a new program was begun in 1970 to (1) compile an exhaustive file of all nonconfidential gravity data for Wisconsin in the same card format and tied to the same data and (2) construct a comprehensive Bouguer anomaly gravity map of Wisconsin. These objectives have been fulfilled except for the omission of two small incomplete surveys contained in master's theses done at Michigan State University (Bork, 1967, and Murrish, 1966).

Acknowledgements

We wish to acknowledge with thanks the cooperation of the Defense Mapping Agency, Aerospace Center (DMAAC), Dr. R.J. Wold of the Department of Geology, University of Wisconsin-Milwaukee, Dr. M.E. Ostrom of the Wisconsin Geological and Natural History Survey, Dr. Paul Sims of the Minnesota Geological Survey, and Dr. N.W. O'Hara of the University of Michigan in supplying data for this compilation. Mr. Elmer Hauer of DMAAC was especially helpful.

Financial support for various phases of the study was provided by the University of Wisconsin, University-Industry Research Committee, the Wisconsin Geological and Natural History Survey, and Mr. E.D. Reinerio, consultant, Madison, Wisconsin. The Madison Academic Computing Center and the University of Wisconsin Geophysical Computing Facility were used for data processing.

We especially wish to thank Miss Sally Ann Griffiths who did much of the tedious work required on the project.

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Compilation of Bouguer Anomaly Gravity Data*

The initial file for construction of the Bouguer anomaly gravity map of Wisconsin consisted of data from 16,118 gravity stations from all sources. Data for 426 stations were excluded because their reported anomaly values were in substantial conflict with adjacent stations or because one or more of the principal facts (position and elevation coordinates or gravity data) were preliminary (IS-5) or incomplete (IS-4), leaving a total of 15,692 stations (Table 1). The areal distribution of stations ranges from approximately one station per square mile in the northwest and in the northeast to less than one station in 50 square miles for some areas in the central part of the state. In addition, several thousand stations in Michigan, Minnesota, Iowa, and Illinois were used for contour control along the state's borders.

Original sources for the data are listed in the Appendix. Data for south and north central Wisconsin were obtained primarily from IS-1 (IS = Immediate Source; refer to page 8), with additional data from IS-2. Most of the concentrated data are from IS-3 in the northeast (Carlson, 1972) and from IS-4 in the northwest (Craddock, et. al, 1969). IS-5 supplied all of the stations in Green Bay.

Table 1 shows the number of Wisconsin stations obtained initially from each source, the number deleted, and the number corrected. Duplicate stations from various sources are counted as one station in the tabulation. Minor uncertainties remain in the final data set. Where two stations were in disagreement but no criteria could be established from the adjacent data for choosing one over the other, both were retained and an average value was used for contouring. Interpolated contours within large gaps in the control also are subject to change. Station locations are shown in the background on the map to indicate the available control.

Table 1

Source and total number of stations used for compilation

IS	Total Initial Stations	Total Deleted	Total Corrected	Total Retained
1	5,603	216	0	5,387
2	67	6	0	61
3	3,448	1	1	3,447
4	6,958	197	171	6,761
5	42	6	0	36
Total	16,118	426	172	15,692

* Prepared by C. Patrick Ervin

Tying the various gravity sets together on a common datum was simplified by the World Relative Gravity Reference Network [Aeronautical Chart and Information Center (ACIC) Reference Publication 25, Department of Defense, Air Force]. This publication includes data on most base stations established by G.P. Woollard for the Bouguer gravity anomaly map of the United States (1964). Most modern surveys originate from one of Woollard's bases. Thus, the Department of Defense (DOD) datum is a means of tying various surveys together and for making comparisons on a worldwide basis. The data for the new Bouguer anomaly gravity map of Wisconsin were adjusted to the DOD datum* using the reference base stations given in the Appendix. The datum shift applied to each of the surveys is given in Table 2.

Table 2

Datum shifts applied to each survey

Immediate Source (IS)	Secondary Source (SS)	Adjustment (mgal)
1	All	None
2	0	-0.01
	1	-0.7
	3	-1.1
	4	-1.0
	5	-1.0
	6	-1.0
	7	-1.1
	8-16	-1.0
3	1	-1.0
4	1	-1.0
5	0	None

It was necessary to develop a standard format for the data file because of differences in accuracy and units of measure used in the original surveys. The format adopted for this study is designed to be sufficiently general to accommodate future surveys of greater accuracy and uses meters instead of feet as the unit for elevations. Table 3 lists units used in each of the original surveys. The number of significant digits shown corresponds to the number recorded in the original data sets, and does not necessarily indicate the true accuracy of the number.

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* The DOD datum has since been readjusted to conform to the International Gravity Standardization Net--1971.

Table 3

Units used in original surveys

	Standard Format	IS-1	IS-2 SS 0	IS-2 SS 1-16	IS-3	IS-4	IS-5
Elevation	0.01 m	0.1 m	1 ft	1 ft	1 ft	1 ft	0.001 m
Coordinates	0.01 min	0.1 min	0.1 min	0.1 min	0.0001	0.1 min	0.01 min
Obs. Grav.	0.01 mgal	0.01 mgal	0.01 mgal	0.1 mgal	0.01 mgal	0.1 mgal	0.001 mgal

The final Bouguer anomaly values were calculated in the normal manner using sea level as datum and densities of 2.67 grams per cubic centimeter for rock and 1.00 gram per cubic centimeter for water. Terrain corrections for local topographic relief were not available but are relatively insignificant in Wisconsin.

Geologic Interpretation*

Distinctive patterns of gravity values divide the state of Wisconsin into three gravitational provinces. (1) The northwestern province is a part of the Mid-Continent Gravity High and is generally bordered on the southeast by the Lake Owen and the Keweenawan thrust faults. This area is strongly anomalous and has arcuate NNE-SSW to NE-SW trends. (2) The northeastern province includes Marinette and Florence counties, the northern portion of Forest County, and extends into adjacent northern Michigan. This province is sharply anomalous along WNW-ESE and E-W trends. (3) The southern province includes the rest of Wisconsin, about two thirds of the total area of the state. It is dominated by broad, low gradient, gravitational features that generally parallel the NE-SW tectonic pattern in pre-Keweenawan rocks.

Regionally, the gravity anomalies correlate very closely with known major structural features as shown on the inset generalized structure map, but a number of significant extensions and modifications are suggested and discussed below. Gravity data indicate no recognizable expression of the Wisconsin-Kankakee Arch. Another principal exception to correlation with structural features is the complete lack of gravitational expression of the thickening section of Paleozoic sedimentary rocks in the southern and expecially the southeastern areas of the state. This is interpreted to indicate that the central and southern parts of Wisconsin are in isostatic equilibrium, a not unexpected conclusion.

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* Prepared by S. Hammer

In the northwestern province, correlation of individual gravity anomalies with mapped geologic structural features is excellent. The Lake Owens thrust fault is represented by a steep, narrow band of gravity contours that show local relief of about 50 milligals (mgals). The sharp N5°W offset of the fault in Washburn County (Dutton and Bradley, 1970) is clearly indicated by the gravity data. The gravitational expression of the offset swings farther west and is perpendicular to the southern segment of the fault. It also is displaced a few miles southwestward of Dutton's locations. To the northeast of the offset, the gravitational expression of the Lake Owen thrust fault becomes considerably weaker and irregular.

The Douglas thrust fault, in the Superior-Bayfield area, also is strongly expressed and detailed by gravity with relief of 40 mgals at the west, decreasing to about 10 mgals near the eastern end before it disappears gravitationally in the south flank of the extremely strong minimum in the Upper Keweenawan trough. One of the lowest Bouguer anomaly values in Wisconsin (-92 mgals) occurs in the Keweenawan trough. A great thickness of low density rock is indicated in the area.

In Wisconsin the Keweenaw fault is indicated by gravity, but its expression is much stronger and sharper eastward into Michigan. On the Keweenaw Peninsula the local gravity relief of the fault is about 30 mgals in a narrow band about two miles (3 kms) wide (Bacon, 1966). This requires that the density contrast across the fault must be limited mainly to rocks of shallow depth (less than 5000 feet; 1500 meters) and implies a minimum density contrast of about 0.5 grams/cc across the fault. A density contrast of this magnitude indicates a major difference in rock type on opposite sides of the fault.

The River Falls syncline, on the east flank of the Mid-Continent Gravity High, is expressed by an asymmetrical gravity low with associated relief of about -40 mgals. The third lowest Bouguer anomaly value (-90 mgals) occurs in Saint Croix County in the River Falls syncline. Gravity data indicate that the northern extension of the River Falls syncline swings sharply eastward in Sawyer County. This change in strike may be tectonically related to the offset in the Lake Owen thrust fault discussed above. In Dunn County there is a strong, eastward gravity embayment from the gravity low closure in the River Falls syncline. This feature is apparently related to an eastward lobe of Keweenawan lavas overlain by Paleozoic rocks as shown by Dutton and Bradley (1970).

In the northeastern province the correlation of gravity and mapped geologic structure is less well defined than in the northwestern province. The Niagara fault is poorly expressed by gravity. To the north, in the vicinity of Crystal Falls and Iron River, Michigan, occurrences of iron-formation and iron ore are very strongly anomalous but any gravitational relation they may have to the Niagara fault is not apparent.

The northeastern province contains many strong gravity anomalies and trends which warrant further study. The strong east-to-west, high-to-low gravity trend in the Amberg area in Marinette County may be significant. The closed gravity high (the -40 mgals contour) east of Blackwell in Forest County appears of special interest.

The third gravitational province includes two thirds of Wisconsin and is generally dominated by broad, gentle NE-SW anomaly trends. There is no recognizable gravitational evidence of major igneous intrusion into the Paleozoic sedimentary cover in this province. Also there is no apparent expression of the Wisconsin-Kankakee arch. The lowest Bouguer anomaly value in Wisconsin (-95 mgals) occurs near Stevens Point in the Wausau-Wisconsin Rapids felsic area of Dutton and Bradley (1970). A great thickness of relatively low density rock (<2.67) is suggested in this area.

In central Price County, there is a steep gravity gradient which is interpreted to indicate an unmapped fault or steeply dipping contact trending NE-SW, with low density rock (probably granite) to the northwest. This area is within and beyond an inferred area of mafic and granitic rocks shown by Dutton and Bradley (1970).

In LaCrosse and Trempealeau counties, several strong, local anomalies are indicated. Additional gravity control is necessary to define details of these features. A similar but large anomaly is present to the southeast in Iowa County. These features could have economic significance.

In south-central Wisconsin, the Baraboo Syncline is characterized by an irregular gravity low. The relation of gravity data and this geologic feature has been investigated and reported in detail by Hinze (1959). Several other anomalies of comparable size and strength exist within the state.

The City of Madison, Dane County, is situated on a broad gravity high which appears to trend NW-SE, perpendicular to the general regional structure in the area. The geologic significance of this anomaly is not known.

References

Bacon, L.O., 1966, Geologic structure east and south of the Keweenaw fault on the basis of geophysical evidence. Am. Geophys. Union Mono. 10, p. 42-55.

Bork, J., 1967, A gravity survey in the vicinity of Mellen, Wisconsin. Unpub. master's thesis, Michigan State Univ.

Carlson, B.A., 1972, Bouguer gravity anomaly map, northeastern Wisconsin. Wis. Geol. & Nat. Hist. Survey, Open File Report.

Craddock, J.C., Mooney, H.M., and Kolehmainen, V., 1969, Simple Bouguer gravity map of Minnesota and northwestern Wisconsin. Minn. Geol. Survey, Map M-10.

Dutton, C.E., and Bradley, R.E., 1970, Lithologic, geophysical, and mineral commodity maps of Precambrian rocks in Wisconsin. Misc. Geol. Inv. Map I-631, U.S. Geol. Survey.

Hinze, W.J., 1959, A gravity investigation of the Baraboo Syncline region. Jour. Geol., 67, p. 417-446.

Murrish, C.H., 1966, An integrated geologic-geophysics study of the Auburndale area, Wood County, Wisconsin. Unpub. master's thesis. Michigan State Univ.

Woollard, G.P., 1964, Bouguer gravity anomaly map of the United States. U.S. Geol. Survey.

APPENDICES

Data Card Format and Code Interpretation

Columns	Information	Example
1-3	State in which station is located	048 (Wisconsin)
4-10	Latitude in degrees and decimal minutes to hundredths (positive north)	+441780
11-18	Longitude in degrees and decimal minutes to hundredths (positive west)	+904216
19	Elevation type	7
20-27	Elevation in meters to hundredths (positive up)	+30042
28-34	Supplementary elevation in meters to hundredths (positive down)	1562
35-42	Observed gravity in milligals to hundredths	98058966
43-47	Code for reference base station (RBS) to which original survey was tied	04806
48-51	Code for source from which data was obtained (Immediate Source)	0002
52-54	Code for original data source (Secondary Source)	003
75-80	Sequence Number	14378

Two elevation types (column 19) are included in this data set. Type (1) is a land station located above sea level. Type (7) is a lake bottom station, also above sea level. For Type (7) stations, a supplementary elevation giving the water depth is included. In this case, the elevation of the water surface is given in the usual elevation columns.

As discussed elsewhere, the observed gravity values have been shifted to the DOD world reference datum.

The base station codes are as follows. The number in parentheses refers to the equivalent ACIC Reference Base Station code designation as given in ACIC Reference Publication 25:

Code	Location
00801	Washington, D.C. (165-0)
02101	Iron River, Mich. (459-4)
02102	Iron River, Mich. (459-0)
02201	Duluth, Minn. (635-3)
02202	Minneapolis, Minn. (0528-1)
02401	St. Louis, Mo. (388-1)
04201	Houston, Texas (270-5)
04801	Madison, Wis. (186-0)
04802	Madison, Wis. (186-1)
04803	Madison, Wis. (186-3)
04804	Madison, Wis. (186-5)
04805	Madison, Wis. (186-A)
04806	Madison, Wis. (186-7)
04807	Wisconsin Rapids, Wis. (4375-1)
04808	Merrill, Wis. (740-2)
04809	Ladysmith, Wis. (4584-1)
04810	Hayward, Wis. (4583-1)

Data files were obtained from five individuals or organizations (Immediate Source or IS). These are (1) Aeronautical Chart and Information Center (ACIC, now called Defense Mapping Agency, Aerospace Center), St. Louis, Missouri; (2) Dr. R.J. Wold, University of Wisconsin-Milwaukee, Milwaukee, Wisconsin; (3) Wisconsin Geological Survey, Madison, Wisconsin; (4) Minnesota Geological Survey, St. Paul, Minnesota; and (5) Dr. N.W. O'Hara, University of Michigan Ann Arbor, Michigan.

Much of the data provided by the above did not originate with the source, but was obtained from elsewhere. Therefore, a Secondary Source (SS) code is used to indicate the origin of the data. These are given below for each IS. Secondary Source designations of the form "Trip AV, Series T", indicate surveys performed under the direction of G.P. Woollard, For data obtained from ACIC (IS-1), their source designation is included in parentheses.

Secondary Sources for IS-1

SS No.	Description
1	(0137) WOOLLARD, G.P. The Gravity Meter as a Geodetic Instrument, Geophysics, Volume XV, No. 1, Jan. 1950
2	omitted as redundant
3	(2094) U.S. COAST & GEODETIC SURVEY USC&GS Survey Area Gravity Surveys
4	(2629) MICHIGAN TECHNOLOGICAL UNIVERSITY Gravity Data Northern Peninsula Michigan
5	(2733) WHALEN, C.T. National Gravity Base Net (NGBN)
6	(2990) U.S. ARMY MAP SERVICE Gravity Base Station Descriptions
7	(2988) U.S. ARMY MAP SERVICE Gravity Data for the State of Illinois
8	(3235) UNIVERSITY OF WISCONSIN Gravity Data for Lake Superior, Michipocoten Island and Lake Michigan
9	(3507) MACK, J.; IVERSON, R.M. Trip AI, Series M
10	(3509) THIEL, E.C. Trip AK, Series T
11	(3514) MANN, V. Trip AQ, Series LM
12	(3517) Hinze, B. Trip AT, Series WH
13	(3519) ALLEN, E. Trip AV, Series EA. Most of this data was deleted for being inconsistent, both internally and with IS-3, SS-1, which is thought to be reliable.
14	(3520) MACK, J. Trip AW, Series M
15	(3524) BACON, L. Trip BC, Series LB
16	(3525) KOENEU (probably KOENEN, K., see IS-2, SS-3) Trip BD, Series AD 1955
17	(3541) SONTAG & FRAST Trip CN, Series AB 1959
18	(3557) BLACK, W.E. Trip DE, Series G
19	(3566) MACK, J. Trip DQ, Series AR

20 (3575) ROSE, J.C.
Trip TT, Series F

21 (3576) HARDING, N.C.
Trip TU, Series F

22 (3577) HARDING, N.C.
Trip TV, Series F

23 (3578) BLACK, W.E.
Trip TW, Series F

24 (3579) BLACK, W.E.
Trip TX, Series F

25 (3587) MUCKENFUS, C.M.
Trip VX, Series E

26 (3588) WOOLLARD, G.P.
Trip WE, Series Z

27 (3590) MEYER
Trip YS, Series W

28 (3591) MEYER & BONINI
Trip YT, Series W

29 (3592) BLACK, W.E.
Trip YU, Series W

30 (3593) BONINI & MEYER
Trip YV, Series W

31 (3594) HARDING, N.C.
Trip YW, Series W

32 (3595) HARDING, N.C.
Trip YX, Series W

33 (3596) HARDING, N.C.
Trip YY, Series W

34 (3597) PLOUFF
Trip YZ, Series W

35 (3598) OSTENSO, N.
Trip ZZ, Series NI

36 (4099) WOOLLARD, G.P.; MACHASKY, L.F.; LONGFIELD, R.L.
Results for a Series of North-South Gravity Control Traverses in the United States, Part 3, Final Report, Oct. 15, 1969

37 (3446) UNITED STATES ARMY TOPOGRAPHIC COMMAND
Wisconsin Regional Gravity Survey, USATOPOCOM, Feb. 1971

38 (3631) UNITED STATES ARMY TOPOGRAPHIC COMMAND
Wisconsin Regional Gravity Survey
USATOPOCOM, Report No. 15D, Apr.-May 1971, WI

39 (3666) UNITED STATES ARMY TOPOGRAPHIC COMMAND
Wisconsin and Northern Michigan Regional Gravity Survey
USATOPOCOM, Report 15E, July 1971

Secondary Sources for IS-2

SS No.	Description
0	WOLD, R.J. Unpublished Wisconsin Gravity Base Station Network
1	THIEL, E.C. Trip AK, Series T
2	ALLEN, E. Trip AV, Series EA, all three stations deleted (see IS-1, SS-13)
3	KOENEN, K. Trip BD, Series AG
4	USC&GS Observed in 1954 and 1955
5	WOOLLARD, G.P. Trip DK, Series Z
6	WOOLLARD, G.P. Trip DL, Series Z
7	MACK, J. Trip DQ, Series AR
8	ROSE, J.C. Trip TT, Series F
9	HARDING, N.C. Trip TU, Series F
10	OSTENSO, N. Trip WF, Series Z
11	BLACK, W.E. Trip YU, Series F
12	BLACK, W.E. Trip YU, Series W
13	HARDING, N.C. Trip YX, Series F
14	HARDING, N.C. Trip YX, Series W
15	PLOUFF Trip YZ, Series F
16	PLOUFF Trip YZ, Series W

Secondary Sources for IS-3, IS-4, and IS-5

IS	SS	Description
3	1	CARLSON, B.A. 1972; Michigan State University, Bouguer Gravity Anomaly Map, Northeastern Wisconsin, available as an open file map from Wisconsin Geological and Natural History Survey, Madison, Wisconsin.
4	1	FRAWLEY, CARRUTHERS 1969; "Northwestern Wisconsin"; included in Simple Bouguer Gravity Map of Minnesota and Northwestern Wisconsin by J.C. Craddock, H.M. Mooney, and V. Kolehmainen, Published by the Minnesota Geological Survey.
5	0	O'HARA, N.W. 1971; Bottom Survey of Green Bay, Wis., for USATOPOCOM.