GLACIAL TILL: A TROUBLESOME SOURCE OF NEAR-SURFACE MAGNETIC ANOMALIES

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ABSTRACT

Potential field geophysicists have been aware of the deleterious effects of glacial till on magnetic maps as far back as the 1940's. However, in the last decade or so, a new generation of geologists and geophysicists entering the potential field arena don't seem to have as solid a footing in geology as the earlier generation, and are unaware of the problems that can arise when performing low-level aeromagnetic surveys over glacial till covered areas. The present paper was written to fill this information gap. I start with a tutorial on glaciation and the glacial processes that resulted in the deposition of vast till sheets over all of Canada and much of the northern United States and explain why these till sheets and glacial drift bodies are magnetic. Then I show or discuss a compilation of 25 examples of magnetic surveys performed in areas covered by glacial deposits that were provided for this study by a large selection of North American geologists, geophysicists and others well known in the profession. The examples cover a wide range of possible magnetic anomaly types created by different shapes and strikes of the glacial sources. In 11 of the 25 examples I document there has been controversy as to the source of the magnetic anomalies, that is, the anomalies were at first incorrectly ascribed to sources other than glacial till. Such controversies clearly accentuate the need for an up-to-date paper on this subject, with examples.

(January 10, 2005)

INTRODUCTION

Knowledge of the magnetic nature of glacial till and its effect on magnetic maps seems to have been lost in the last few decades, even though it is more important now than ever due to the present emphasis on low-level aeromagnetic surveying for petroleum exploration, i.e. surveys where the ground clearance is 150 m or less. In 1940, Nettleton (p. 206) referred to "troublesome" problems with magnetics in glacial areas; in 1946, Heiland (p. 373) stated: "Magnetic interference may occur... by magnetic rocks in glacial drift;" and in 1951, Vacquir stated (p. 1): "There is some benefit [to be] derived from removing the magnetometer a few hundred feet above glacial till and other near-surface magnetic disturbances..." However, today one never hears about problems resulting from low-level flying over areas of glacial deposits, although they many times occur without being recognized. Such problems can be a strongly limiting factor in the accuracy of interpretations of magnetic data for near-surface magnetic sources and for any attempt to map sources within the sedimentary section via so-called HRAM (High Resolution Aeromagnetic) "depth slicing" methods.

First, I will review present knowledge of Pleistocene glaciers and glaciation throughout the northern hemisphere. Glaciation earlier than Pleistocene occurred in the Pennsylvanian/Permian and Proterozoic periods, but is not considered here, as the early glacial deposits are of limited areal extent, widely scattered, mostly eroded, and do not pervasively cover the present land surface. After this tutorial review of Pleistocene glaciation I will show illustrations of, and discuss, the 25 examples of magnetic anomalies over glacial till that I have compiled for this report. Some of these examples are from my own files but most have been obtained from a literature search and by canvassing friends and colleagues in the mining and petroleum exploration industries and at universities and geological surveys in the United States and Canada as far back as 1991.

Figure 1. Maximum extent of Pleistocene glaciers and ice sheets in the northern hemisphere. From Price, 1973.

This compilation will be followed by a brief discussion of the consequences of glacial till anomalies to modern-day computer interpretation schemes and a suggestion on how to attenuate the effects of these anomalies. In anticipation of questions on the latter point (see last section), the surest way to ameliorate the problem is to fly aeromagnetic surveys at least 300 m above ground level, or higher, in areas known to be covered by glacial till.

BRIEF TUTORIAL ON PLEISTOCENE GLACIATION

Mountain glaciers, with their conspicuous lateral and terminal moraines, were observed from the earliest days of geology in the 1600's and 1700's, but continental glaciation was not recognized until the early 1800's. The name most often associated with glaciation is that of the Swiss geologist Louis Agassiz (1807-1873), who became convinced of its validity in 1836 after discussions and a field trip with another pioneering Swiss geologist, Johan von Charpentier, the principal proponent and developer of continental glaciation at the time. Agassiz was president of the Helvetian [Swiss] Society of Natural Science and a prolific writer and speaker, and was thus able to convince many of his reluctant colleagues, both on the continent and in the British Isles of the reality of gigantic ice caps covering all of northern Europe during the Pleistocene period, similar to present day ice caps over Greenland and Antarctica. In 1847, Agassiz left Europe and accepted a professorship at Harvard, thus transferring his work on continental glaciation across the Atlantic and giving a strong impetus to studies of glaciation in North America, which he continued until his death in 1873. By the turn of the 20th century, glacial studies by many geologists on both continents had established the boundaries of glaciation in the northern hemisphere, much as they are shown in Figure 1 (taken from a 1973 Scottish textbook). By 1915, studies in North America had documented the presence of two principal ice sheets, the

"Labrador" on the east and the "Keewatin" on the west that covered almost all of Canada and extended into the northern United States (Fig. 2). Where the two sheets coalesced, as they did in the last glaciation, a single sheet, the "Laurentide" resulted (Fig. 3). Rough calculations of the thickness of ice in this sheet based on crustal rebound in the Hudson's Bay area are approximately 2800 m (9000 ft.) (Zumberge, 1978). However, these calculations assume that the crust was in isostatic equilibrium with the ice, which it undoubtedly wasn't due to the long time-constant involved, so this figure could be too low by a considerable amount. The two present icecaps, Antarctica and Greenland, have, at the present time - not a glacial period - approximate thicknesses of 4000 m (13,000 ft.) and 3000 m (9,800 ft.) respectively (Meier, 1978). A great thickness of ice ensures that the ice flows long distances from the accumulation center, although a thickness of only 60-100 m (depending on temperature) is sufficient for flowage to commence, a depth common in many mountain glaciers.

The recent map of Figure 3 (Martini, et al, 2001) updates and modifies the boundaries of North American glaciation and verifies the thoroughness of the early work. In Figure 4, I show the extent of the outcropping igneous and metamorphic rocks of the Canadian shield, revealing that the principal accumulation centers of the glaciers in North America are underlain by these magnetic rocks. Glaciers remove igneous and metamorphic rocks from the outcrop by a process called "plucking" or "quarrying." As the glacier moves, these quarried blocks and boulders, as well as the soil and alluvial materials lying on the surface of the ground, especially in river drainages, lakes, etc., including previous glacial materials, become incorporated into the glacier. Thus, it is apparent that all continental glacial material in North America must contain igneous and metamorphic materials. When the glacier melts, those materials are left behind as tills, drumlins, etc. and are redistributed and reworked as kames, eskers and river channel deposits

Figure 2. Extent of Pleistocene Glacierization of North America. From von Engeln, 1949, after R. S. Tarr and L. Martin, 1915, College Physiography, MacMillan.

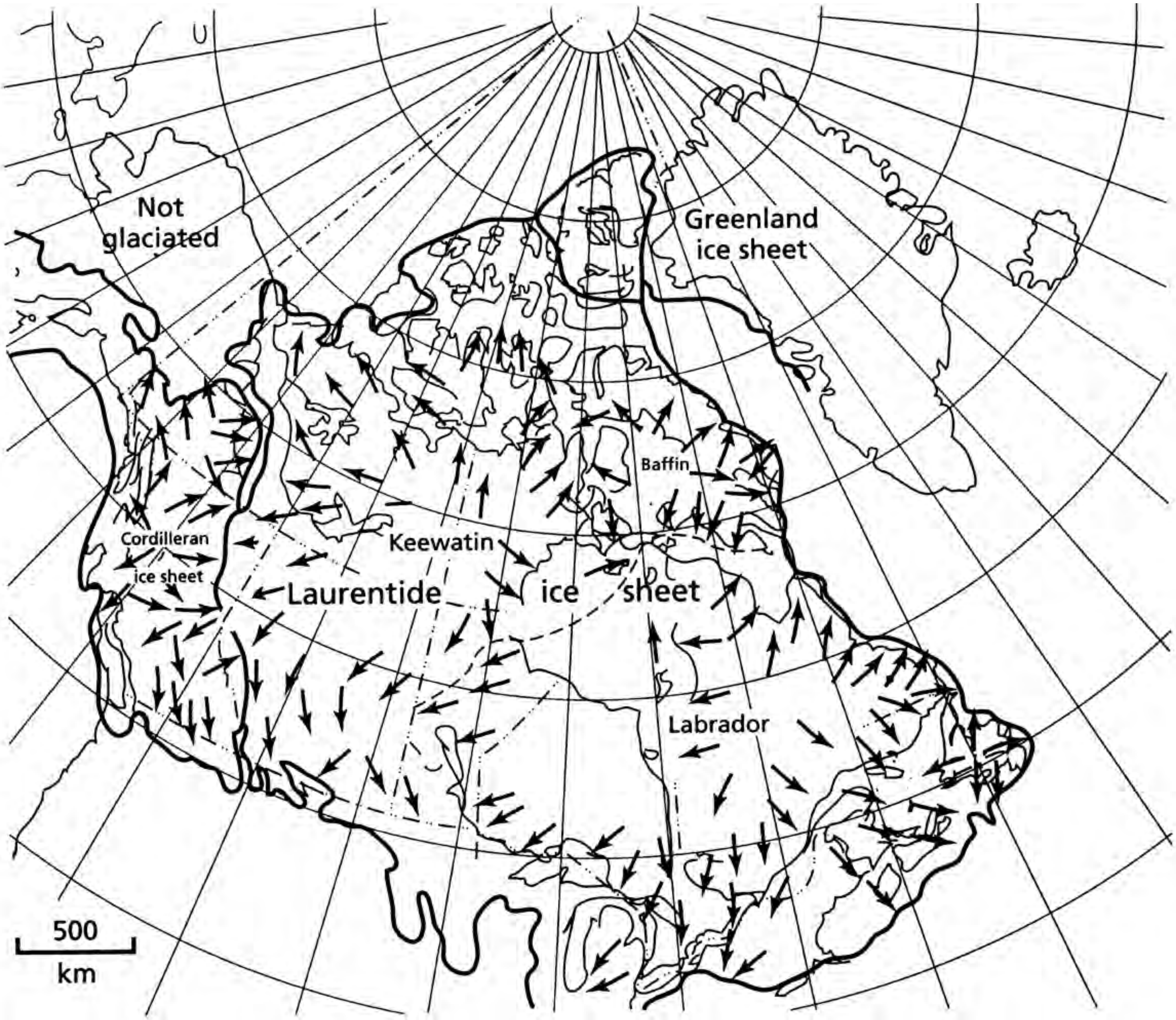


Figure 3. The Pleistocene ice sheet ("Laurentide ice sheet") of North America. From Martini, et al, 2001.

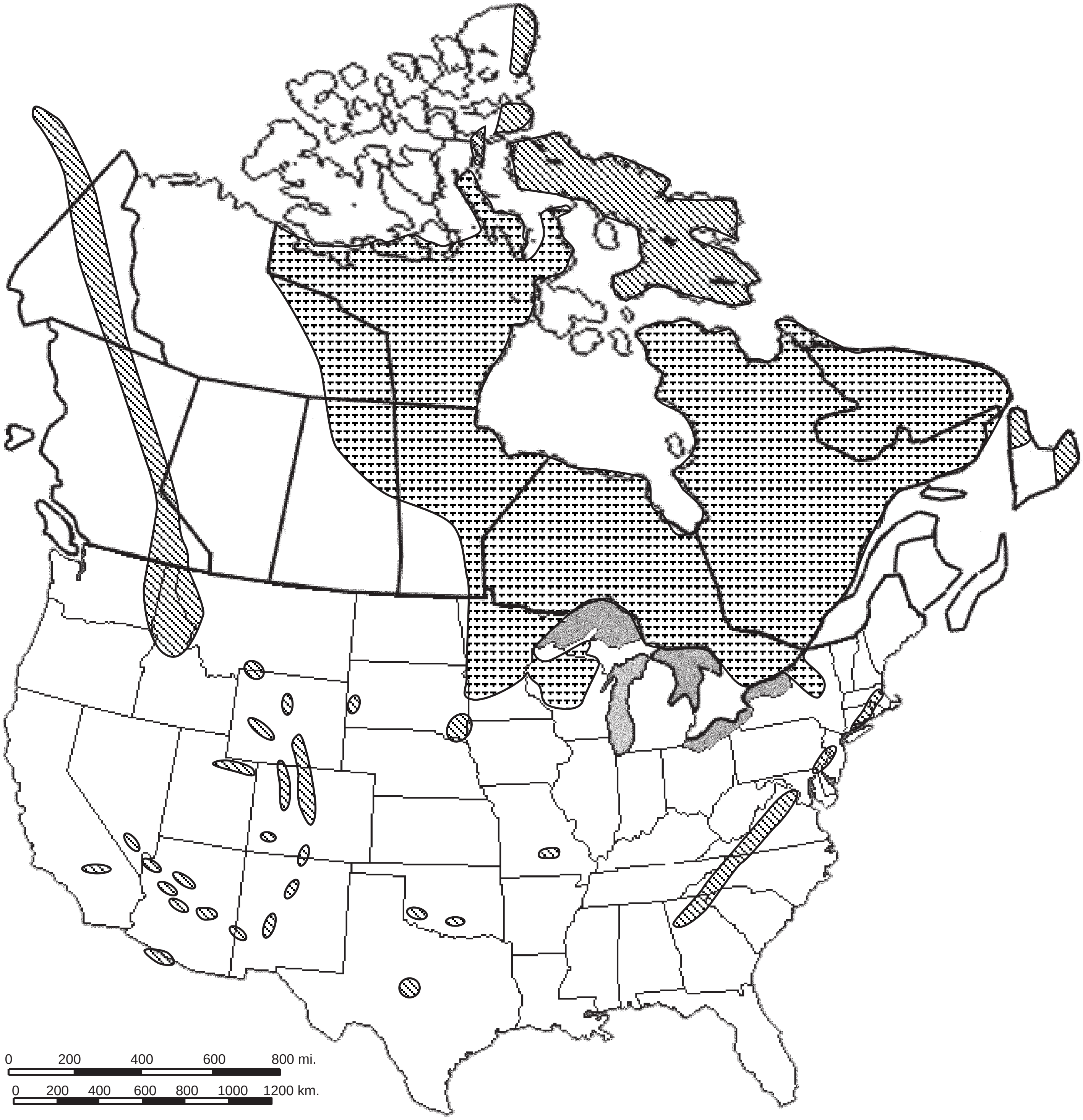


Figure 4. Areas of exposed Precambrian rocks in North America. Note that main accumulation zones of continental glaciers are underlain by outcropping Precambrian rocks. (Compare with previous figures)

of various kinds.

In Figure 5 are photographs of some of the unreworked glacial till in moraines in Canada. They all contain varying percentages of unsorted and unstratified clay, silt, sand, pebbles, and boulders. Figure 6 is a photograph of an esker, which is the material left from a river flowing under, through, or on top of, a glacial sheet. This reworked material is more concentrated in the larger fractions and thus has a higher percentage of boulders and pebbles (and hence is more magnetic) than moraine. Figure 7 shows pebble counts of 3 overlapping glacial drift sheets near the Montana-North Dakota-Canada boundary. All three contain igneous ("granitic") and metamorphic pebbles, some more than others, but in two of the drift sheets, there is a large component of carbonate rocks (limestone and dolomite). The reason for this is apparent in Figure 8. The glaciers moved across extensive outcrops of Ordovician, Silurian, and Devonian carbonates on the southern edge of the Canadian shield before depositing their loads far to the south in the Montana-North Dakota-Canada boundary area (lower left corner).

Studies of glaciers and glacial processes did not stop with Agassiz in the 1800's, but continued with many others, including Richard Flint, the most prolific of the glacial geologists in the mid-1900's, and still continue to the present day. Figure 9 shows a detailed succession of "end" moraines resulting from Wisconsin-aged glaciation mapped in Illinois in the 1990's, for example, and Figure 10 shows detailed mapping of various ages and types of moraines mapped during the same period in Ohio. Figure 11 shows advances in the dating of glacial epochs. In the mid-1900's, there were four accepted glacial divisions in North America ("Old Divisions"), and the data in Figures 7, 10, and 12 correspond to these divisions. However, newer studies, based on modern age-dating techniques, reveal at least 10 different glacial pulses in the Pleistocene going back approximately 800,000 years and an earlier one in the Pliocene (Fig. 11).

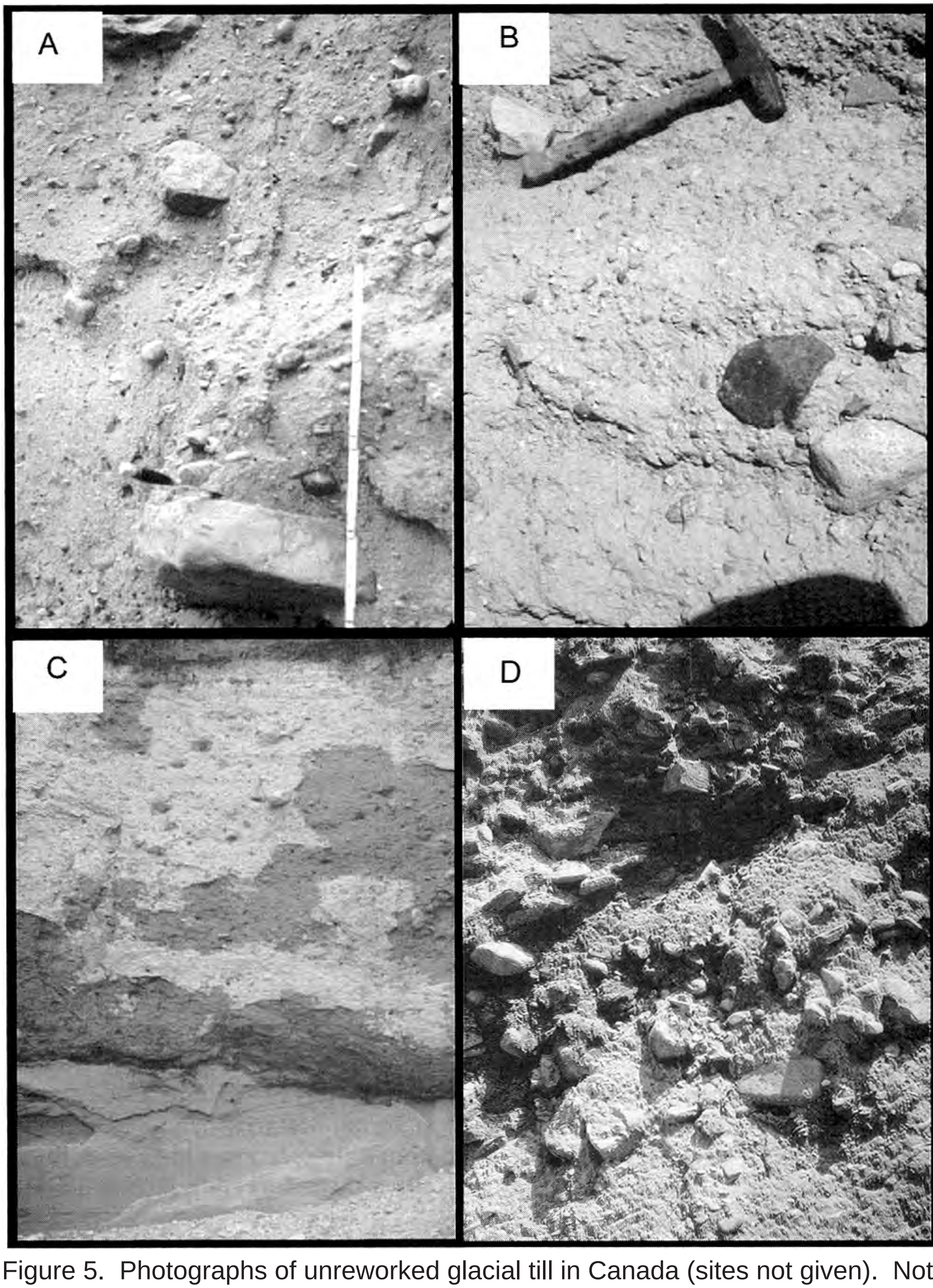


Figure 5. Photographs of unreworked glacial till in Canada (sites not given). Note the unsorted, unstratified nature of the till. All unreworked till contains pebbles, boulders and clay in varying proportions. From Martini, et al, 2001.

Figure 6. Photograph of glacial till in an esker at Hopeville, Ontario, Canada. Note the large percentage of pebbles and boulders resulting from reworking of the till by fluvial processes. From Saunderson, 1982.

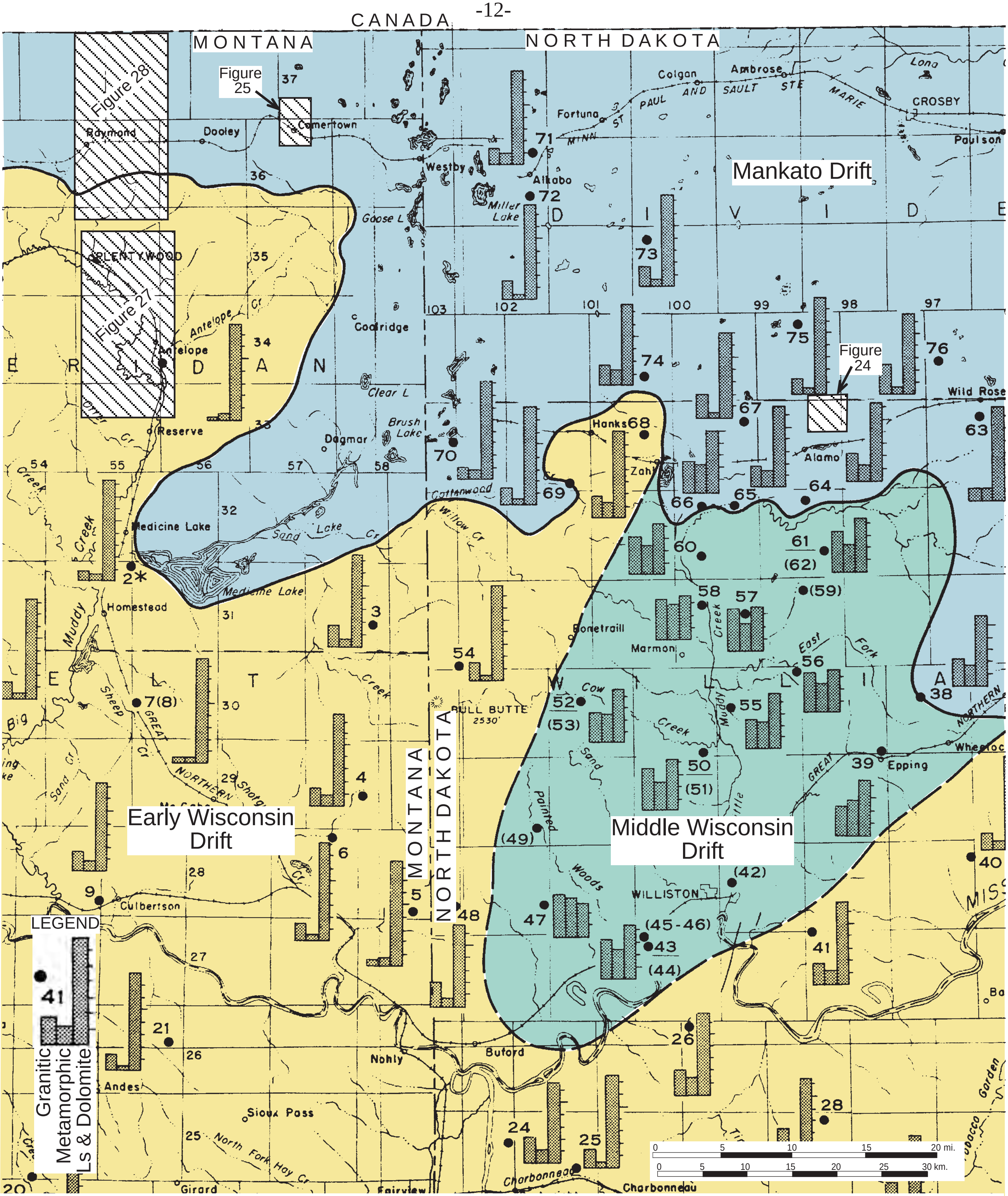


Figure 7. Pebble count analyses of glacial drift sheets, NW N. Dakota, NE Montana. Note that first two columns, granitic and metamorphic pebbles, are magnetic, whereas last column, limestone and dolomite, is not. Mankato drift is late Wisconsin in age. From A. D. Howard, USGS Prof. Paper 326, 1960, Plate 5.

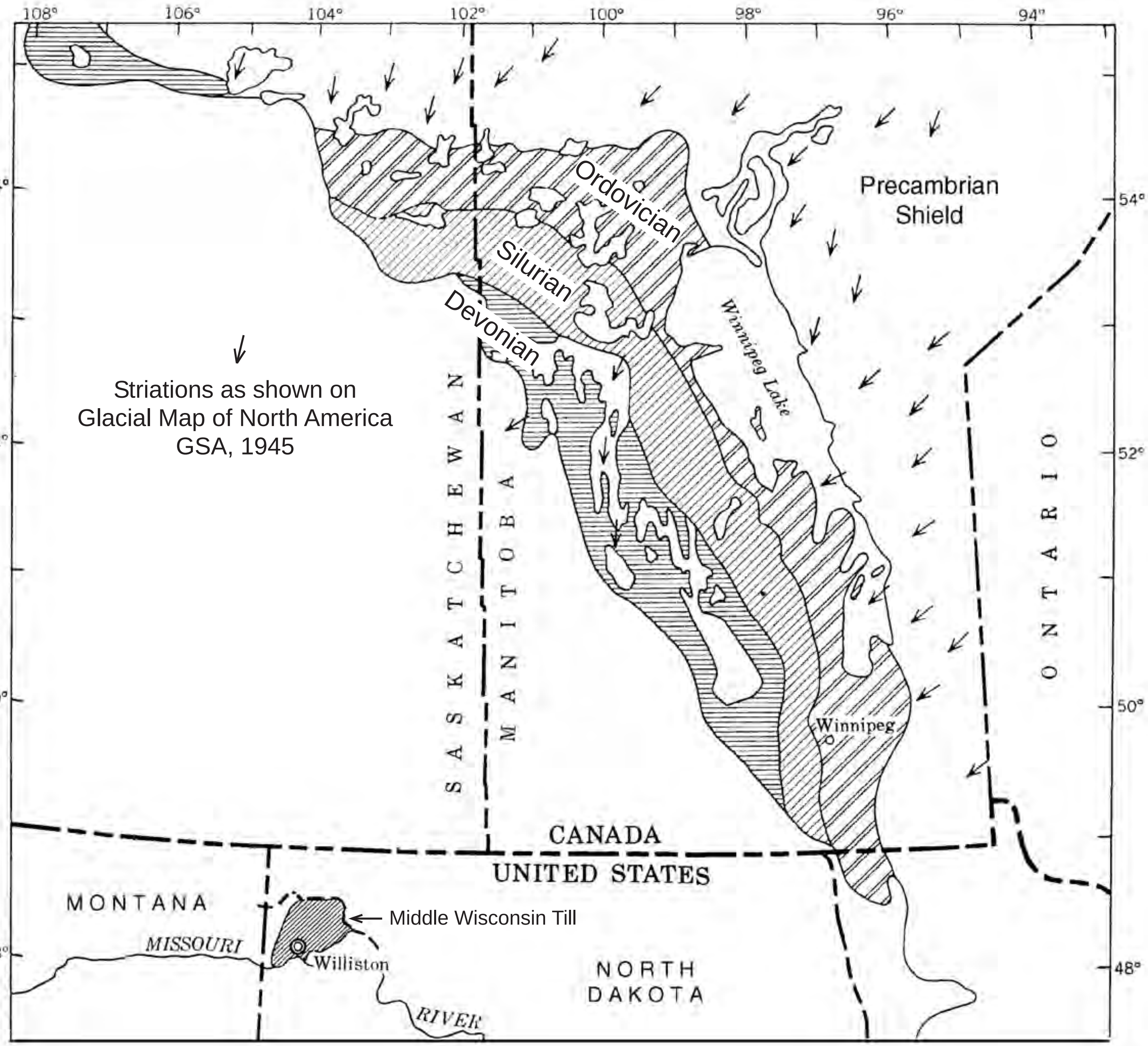


Figure 8. Paleozoic rock subcrop in Manitoba and Saskatchewan. Note arrows showing direction of movement of the Keewatin ice sheet. The glaciers pick up limestones and dolomites when overriding the Paleozoic rocks in addition to the igneous and metamorphic rocks they are already carrying south from the Canadian shield. From Howard, 1960.

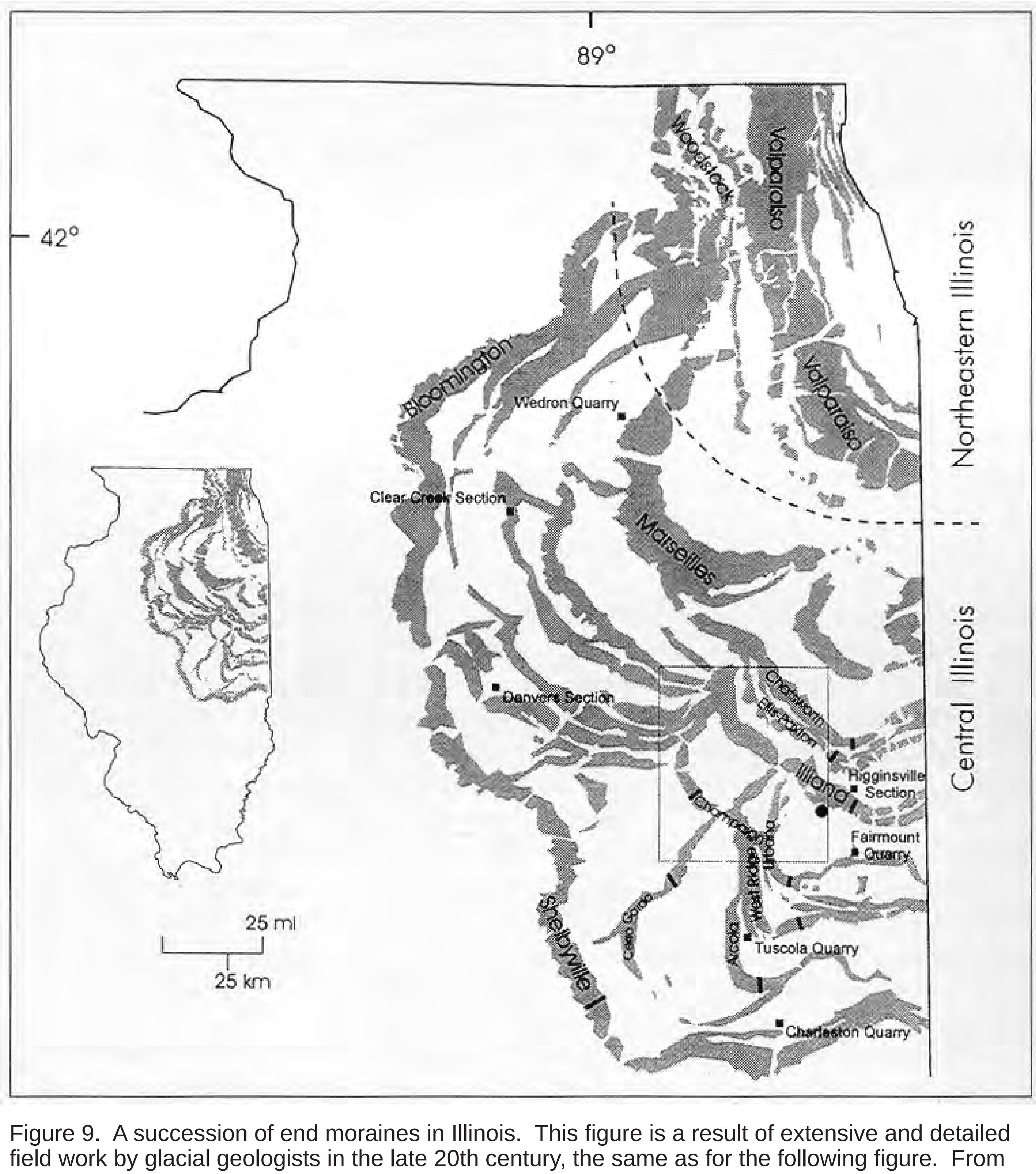


Figure 9. A succession of end moraines in Illinois. This figure is a result of extensive and detailed field work by glacial geologists in the late 20th century, the same as for the following figure. From Johnson, 1999.

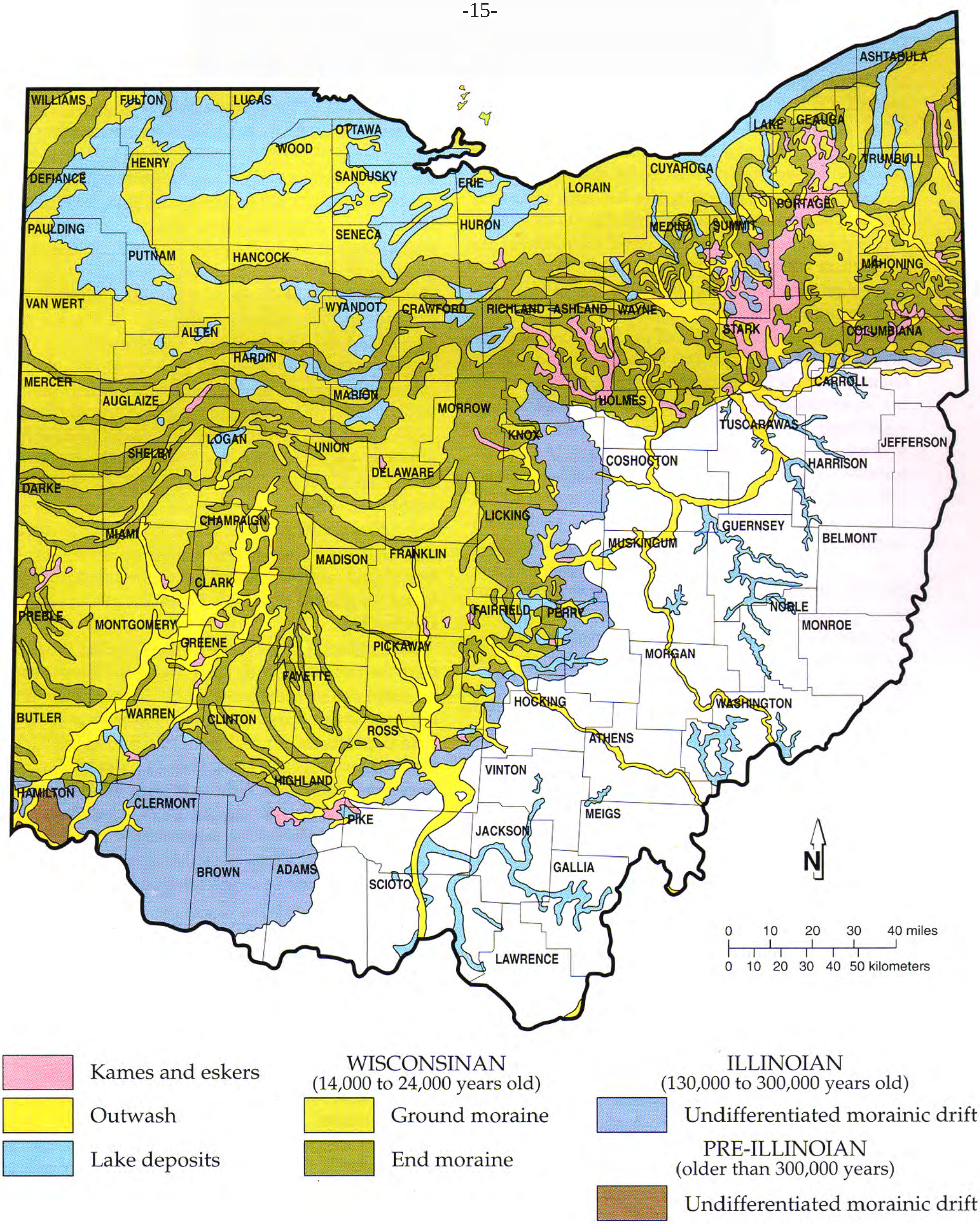


Figure 10. Glacial deposits of Ohio, produced by the Ohio Geological Survey, 1995.

Old Divisions

North America	
Glacial	Interglacial
Wisconsin	
	Sangamon
Illinoian	
	Yarmouth
Kansan	
	Aftonian
Nebraskan	

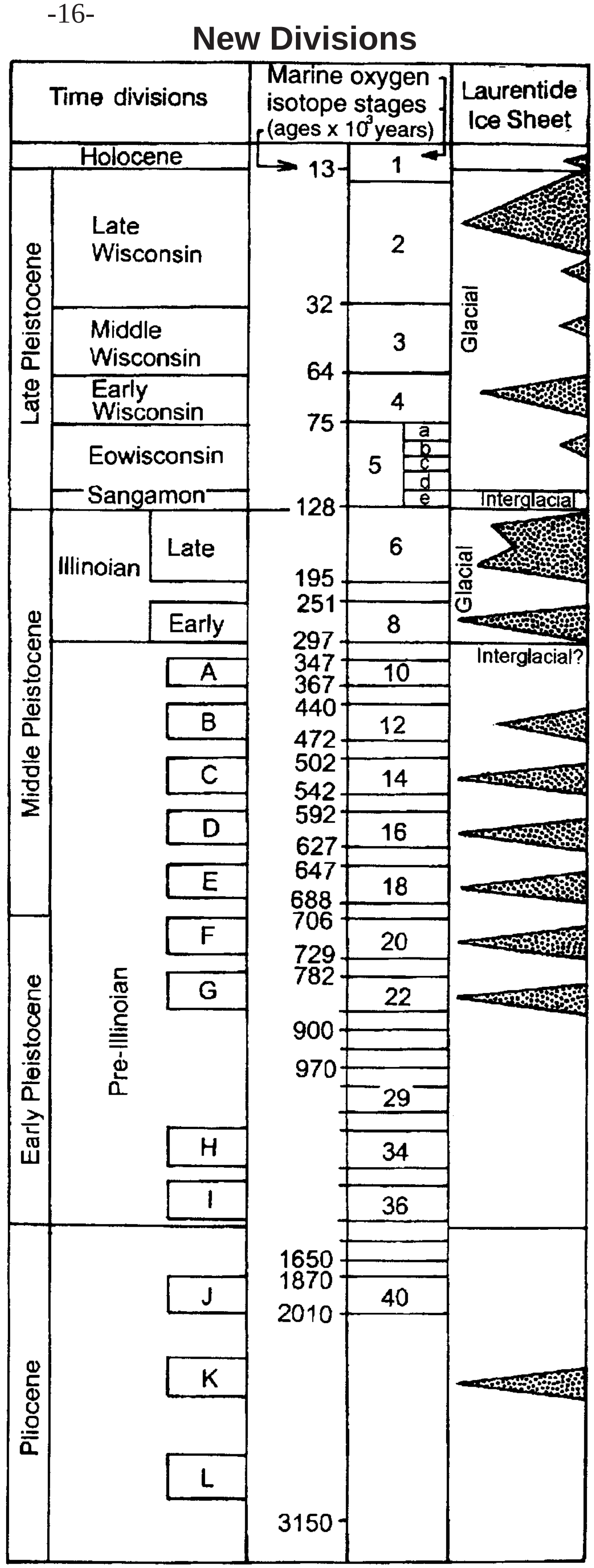


Figure 11. Old and new divisions of Pliocene-Pleistocene ice ages in North America. Note that the new work shows 11 or more glacial advances compared to the 4 shown previously. From Martini, et al, 2001.

Note that between each of the glacial pulses, there was an interglacial period, now popularly called "global warming," a natural phenomenon that has occurred many times in the last one million years.

To summarize this section for purposes of the present study, glacial till in North America contains varying amounts of igneous and metamorphic rocks and hence is magnetic. There appear to be few or no exceptions, so there is little or no non-magnetic glacial till. Figure 12 shows the extent of the till in the United States and southern Canada, and a comparison of this figure with a map of the petroleum basins in North America reveals that till covers the following:

1) the northern one-third of the Appalachian Basin
2) 100% of the Michigan Basin
3) the northern two-thirds of the Illinois Basin
4) the northern two-thirds of the Williston Basin
5) 100% of the Western Canada Basin.

EXAMPLES OF MAGNETIC ANOMALIES OVER GLACIAL TILL

A quick review of the literature on glaciation reveals a large number of glacial landforms with characteristic names that I decline to discuss in detail, partly because of the sheer volume of this material and partly because of conflicting and overlapping terminology. The interested student can pursue this subject further if he desires. The references at the end of the paper are a good starting point. I will only discuss the pertinent terminology as it arises in the examples of magnetic anomalies that follow.

First, I will attempt to briefly and schematically show some of the main types of magnetic anomalies to be expected in areas of glacial till, starting with the most simple and proceeding

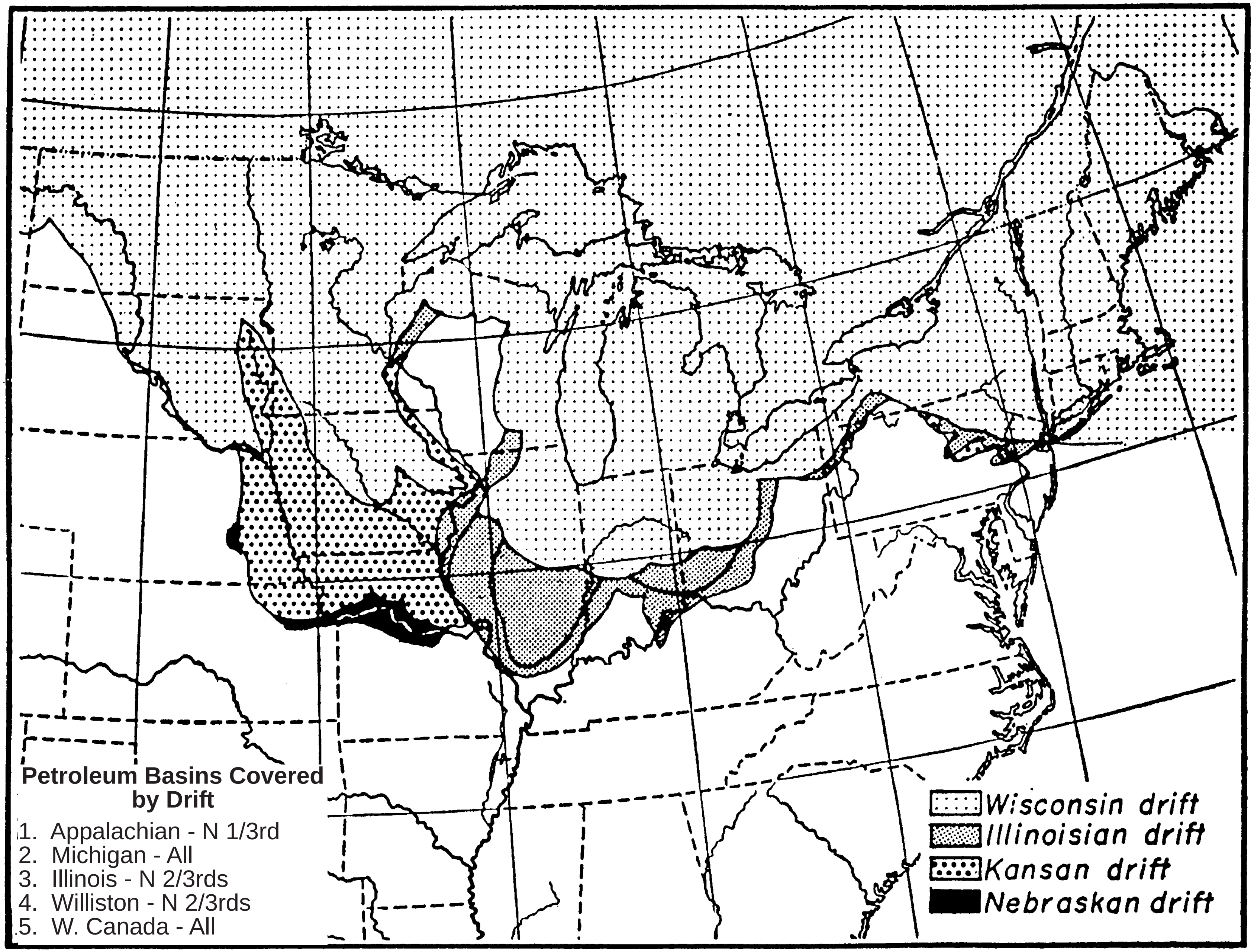


Figure 12. Glacial drift sheets of the central and northern United States. From von Engeln, 1949, after Richard F. Flint, 1947, Glacial geology and the Pleistocene epoch, J. Wiley, New York, 589 p. This 56-year old map shows the age divisions of the glacial drift as worked out in the mid-20th century.

to the more complex. They appear in Figure 13. Examples GL1, GL2, and GL3 are, in a sense, the same from a magnetics standpoint, all three being representable by long horizontal cylinders (see Gay, 1965, for anomaly curves). Eskers occur above the land surface and are more magnetically concentrated than till, as mentioned previously. Infilled valleys (GL2) and rivers with resorted glacial boulders (GL3) are similar in response, but the latter have been subjected to post-glacial processes and have a higher magnetic susceptibility. Actual present-day drainages may contain a combination of the two.

Where moraine has been completely removed by a young river (GL4), the inverse of 1, 2, and 3 occurs. I thought this type of occurrence was probably rare and mainly theoretical, but an example was contributed to this study (Fig. 33) by Canadian geophysicist Scott Hogg (Example E13).

Where blanket moraines (end moraines, ground moraines, etc.) cover buried valleys filled with glacial debris, the underlying material, particularly if it is comprised of resorted boulders, will show through as a magnetic high (GL5).

When carrying out ground magnetic surveys or very low-level airborne surveys in moraine-covered or drumlin-covered areas, the magnetic profiles will mimic the surface of the ground, generally, with little reflection of the underlying topography beneath the till (GL6). However, the underlying topography can be important if there are large valleys or hills present, or the survey is flown higher, in which case the magnetic profiles will mimic the thickness of the till (GL7). However, herein lies the problem. We almost never know the configuration of the underlying topography, hence cannot construct a reliable till thickness map, hence cannot predict the magnetic response of the till.

Types of Magnetic Anomalies over Various Glacial Landforms (GL)

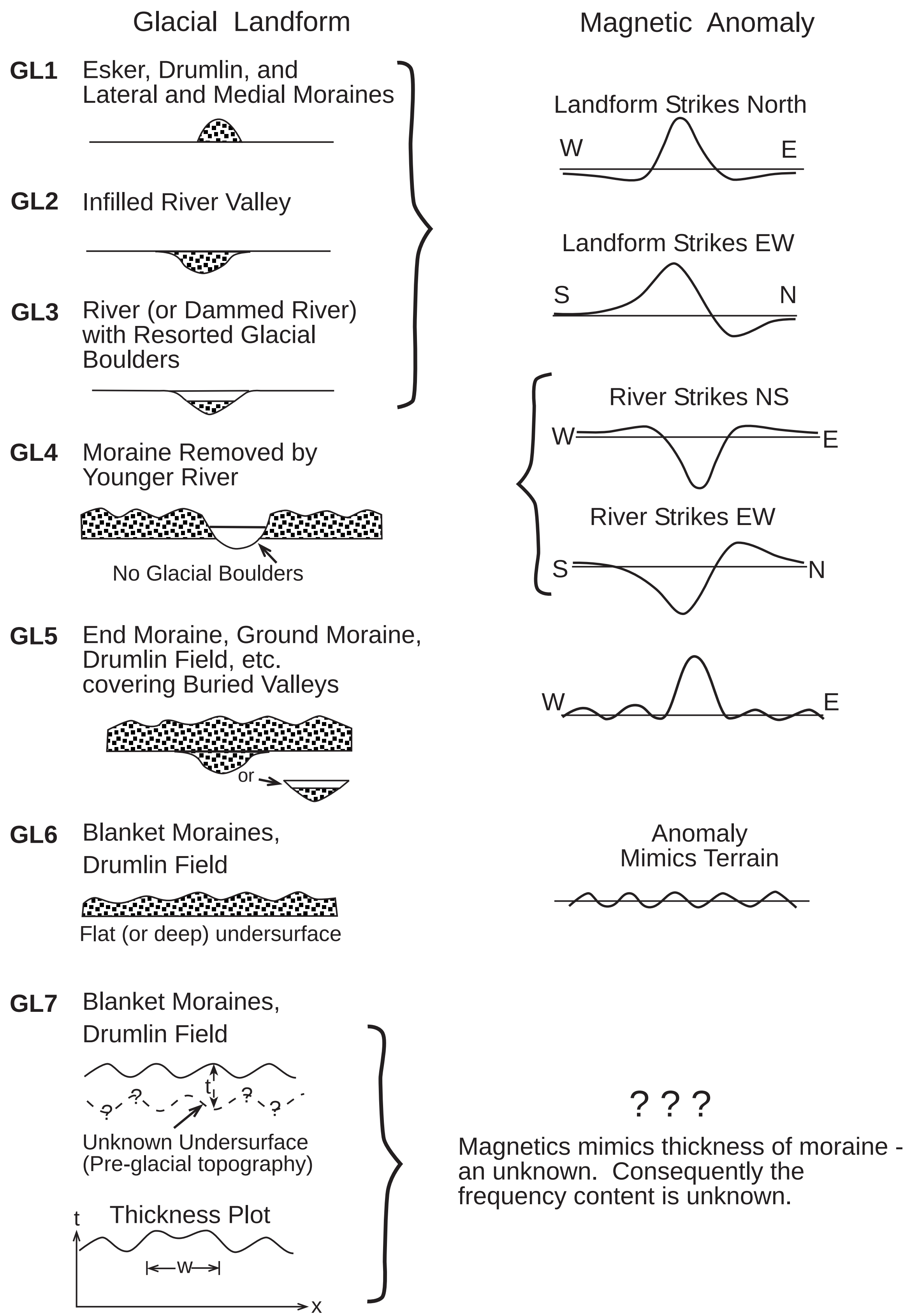


Figure 13. Types of magnetic anomalies over various glacial landforms. Shapes of the anomalies vary not only with the type of landform, but also with its strike.

For example: a project the author carried out in southern Michigan required removing glacial till effects from magnetic maps. A set of "Glacial Drift Thickness Maps" of each county involved was purchased from the Michigan Department of Natural Resources (the only state that publishes such maps?) and thus: problem solved! Or so we thought. However, the drift thickness maps are extremely undersampled and were of no value for calculating magnetic anomalies. They can be misleading for those who do not know they are based on a broad scattering of water wells and even more scattered petroleum wells. Only the latter penetrate to the bottom of the till and very few of the former. Furthermore, even if we had obtained an accurate till thickness map, a further level of complexity would have been the inhomogeneous magnetic nature of the till itself.

In Figure 14 appear the locations of the magnetic examples obtained for this study. They are numbered according to their appearance in this paper. Note there are 7 published examples (indicated by “P”), 18 unpublished. Eleven examples are from the continental U.S., ten from Canada, three from Alaska and one from the North Sea. More examples would be appreciated from readers for a later, updated version of this paper, or an addendum.

Example E1. The first example I show is the most well-documented case history I have obtained. There is an airborne magnetic map (Fig. 15a), a ground magnetic map (Fig. 15b), a modelled magnetic profile (Fig. 16), and a drill hole (Fig. 15a) on a lake adjacent to the Balmat zinc mine in upper New York state (Fig. 17). This material was all supplied by consulting geophysicist Chris Ludwig of Denver. In the 1970's the magnetic anomaly was thought to be an intrusive with possible accompanying orebodies, but Ludwig noted its exact coincidence with the lake and thus suspected glacial boulders. Support from the modelling results and an earlier drill hole (1929) found in the archives that penetrated large igneous and metamorphic boulders proved him right. On my Figure 13, this is classified as GL3, a dammed river drainage with

Figure 14. Locations of documented magnetic anomalies over glacial till collected for this paper. Numbers by each location may be used to reference the examples in the text.

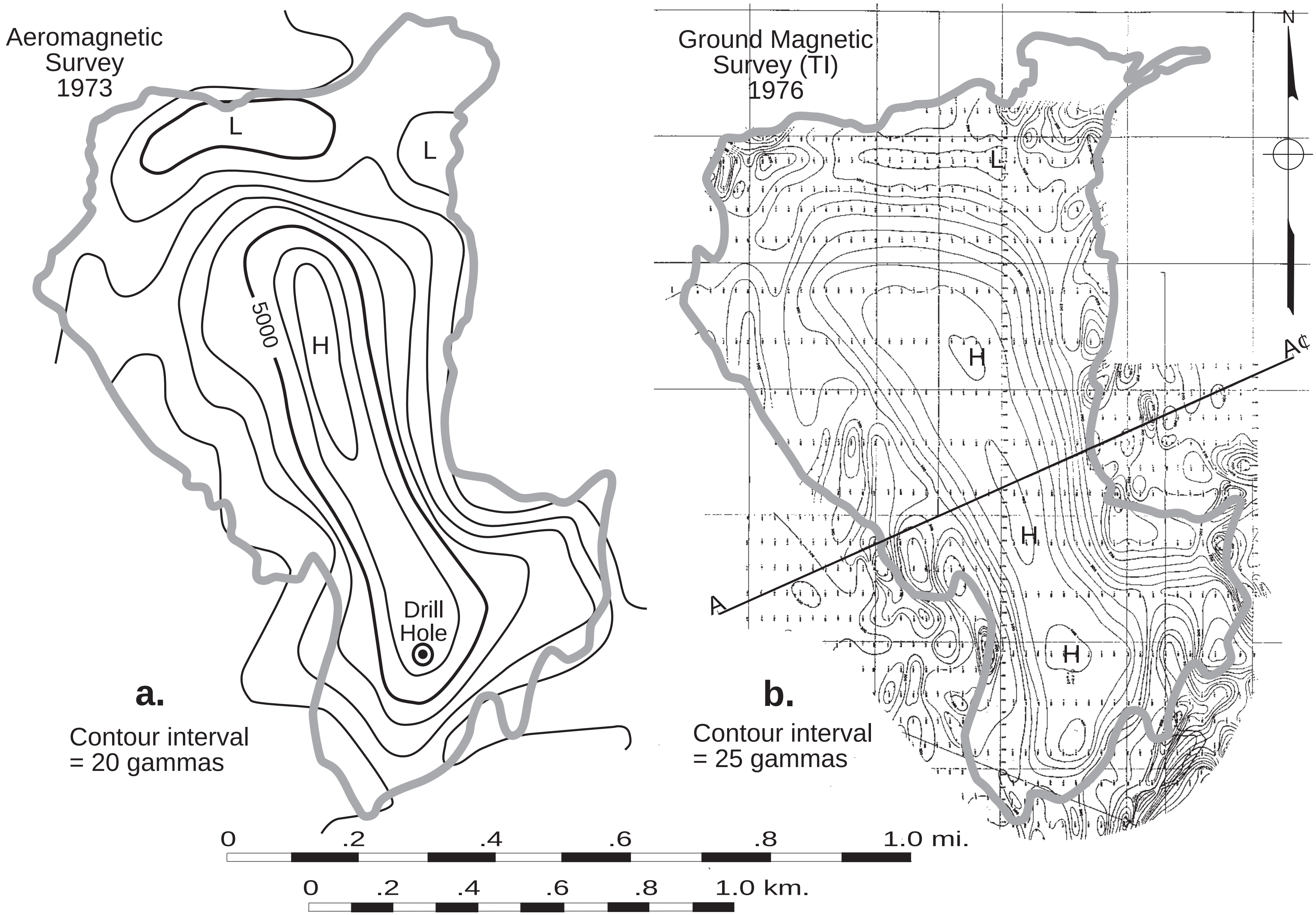


Figure 15. Magnetic surveys over Lake Sylvia, Balmat mine area, St. Lawrence Co., New York. The drill hole encountered scattered igneous and metamorphic boulders throughout its whole depth resulting from reworking of glacial till. The hole was abandoned in boulders at 365 ft. Maps provided by Chris Ludwig, consulting geophysicist, Denver, CO, 2002.

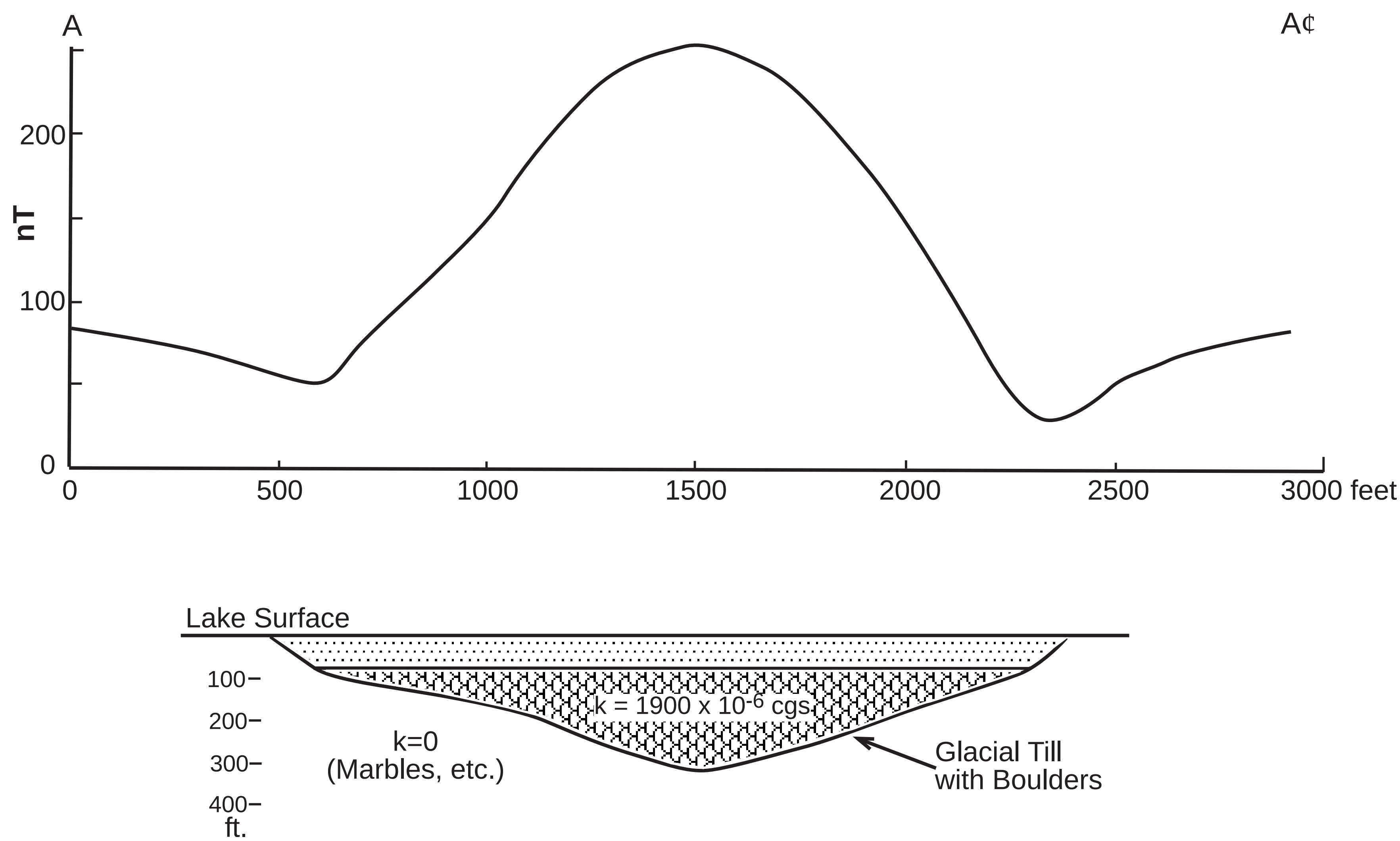


Figure 16. Model results from ground magnetic profile on frozen Lake Sylvia, St. Lawrence Co., New York. Modelling by Chris Ludwig, consulting geophysicist, Denver, CO, 2002.

resorted glacial boulders.

Example E2. The next example is geologically/geophysically similar to example E1, but with a different history. The Black River/Trenton oil and gas play in New York, Pennsylvania, and West Virginia in the late 1990's created a lot of work for the potential field community, and one of the resulting aeromagnetic surveys was flown over the southern Finger Lakes region of New York (Fig. 17). Figure 18 shows a portion of this survey and a magnetic high that exactly coincides with Lake Cayuga. The same survey revealed that the adjacent Lake Seneca also has a coincident magnetic high, as do several other present-day rivers and lakes, but in addition, there are similar long, sinuous magnetic highs <u>not</u> coincident with present-day drainages. All lakes and drainages are part of a Pleistocene drainage system occupied by large post-glacial rivers. The magnetic map was supplied by the late Ed deRidder of Pearson, deRidder, and Johnson of Denver, Colorado.
(Fig. 13, GL3)

Example E3. Dropping to ground level, we now look at surface magnetic profiles over two eskers in Ingham County, Michigan. This was a graduate thesis by L. J. Onesti supervised by Wm. J. Hinze at Michigan State University and published in the GSA Bulletin in 1970 (Fig. 19). Note the noisy magnetic highs on each of the two lines over eskers labelled A & B. The noisy nature of the profiles is due to the highly inhomogeneous character of the till, which mainly results from the presence of boulders of magnetic rocks close to the surface and near the magnetometer. A photograph of an esker appears in Figure 6 in this paper. This example was provided to the author by Prof. Hinze. (Fig. 13, GL1)

Example E4. Immediately south of Ingham County, Michigan, in Jackson, Calhoun and Hillsdale Counties is located the prolific Albion-Scipio oil field. Low-level magnetic surveying

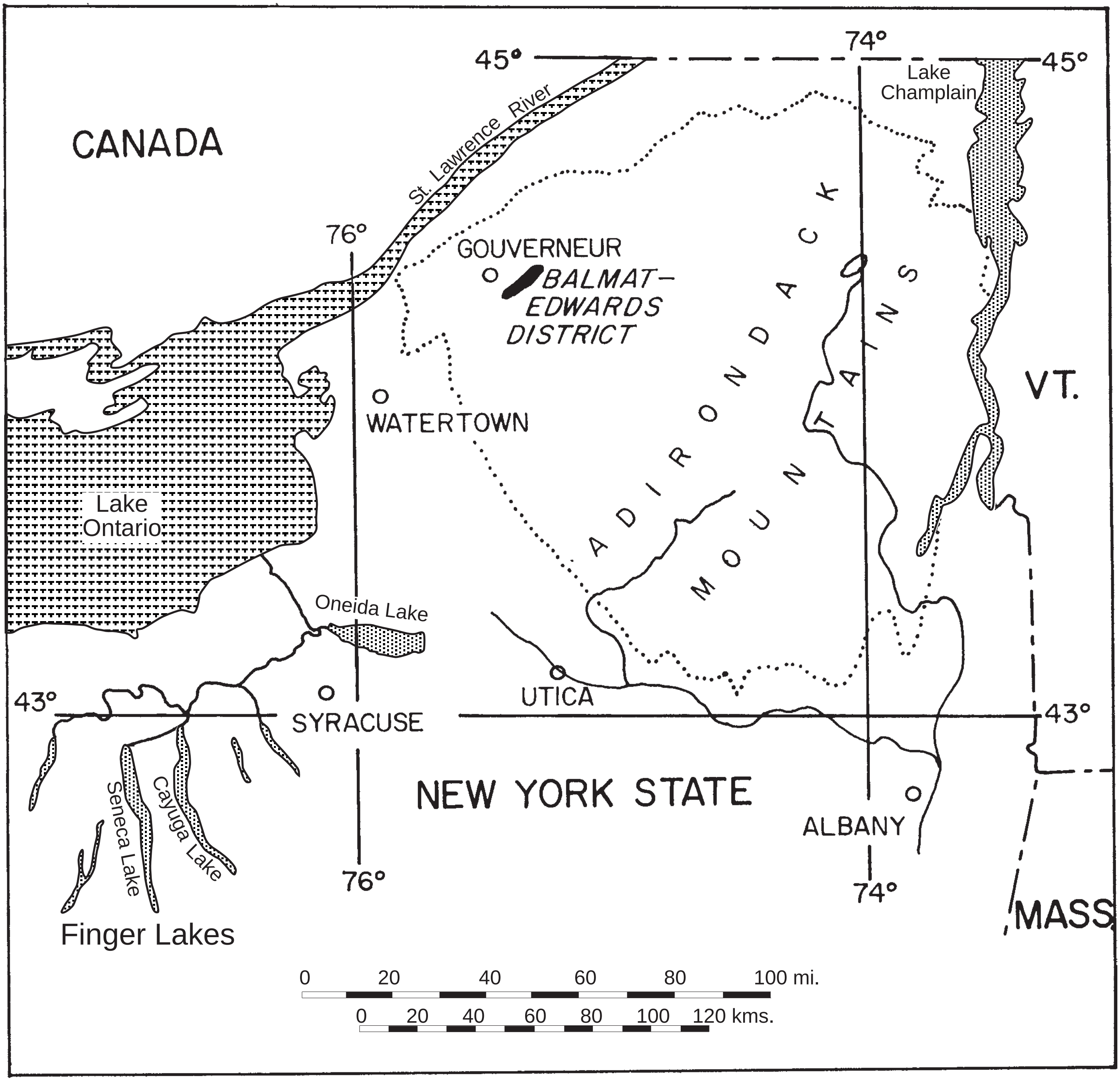


Figure 17. Map showing the locations of the Balmat mining district (Figs. 15 & 16) and of Lake Cayuga, one of the Finger Lakes (Fig. 18). From Lea and Dill, 1968.

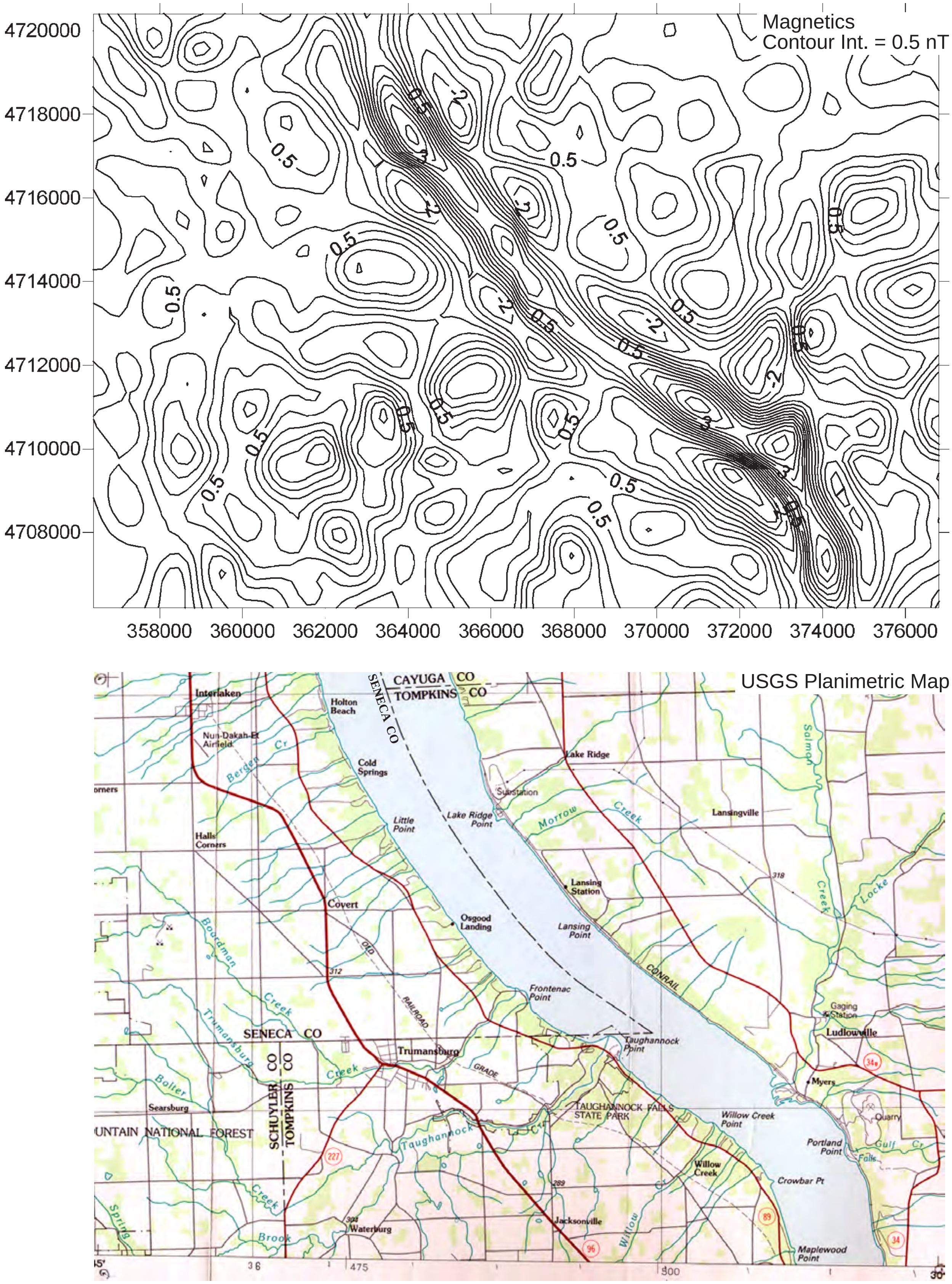


Figure 18. High-frequency aeromagnetic plot of southern Lake Cayuga area, W. New York State, compared to drainage and culture. Data provided by the late Ed deRidder, Pearson, deRidder & Johnson, Inc., Denver, CO, 2002.

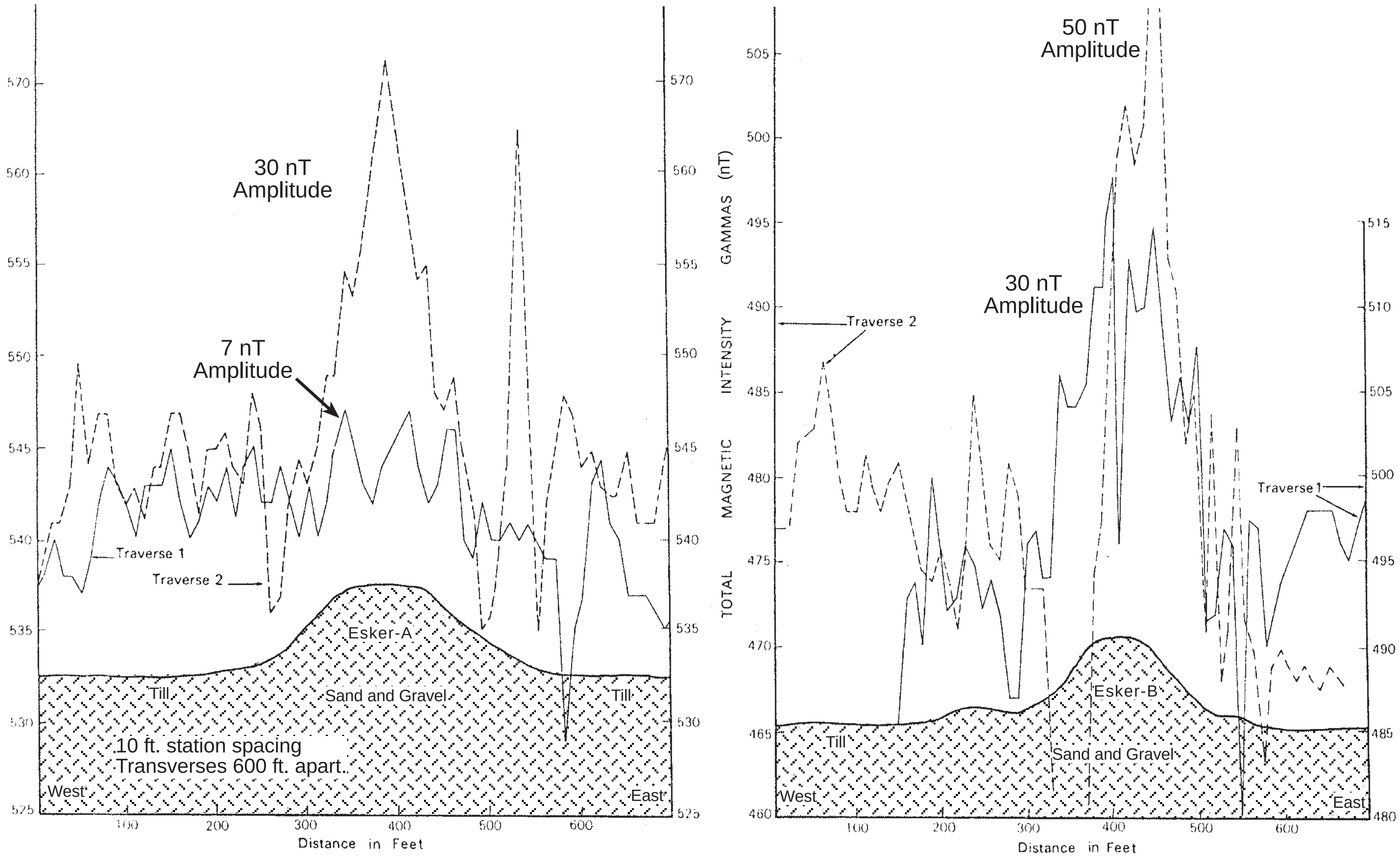


Figure 19. Magnetic profiles over eskers, in Ingham County, Michigan. From Onesti and Hinze, 1970. Smoothing operators would greatly improve comprehension of the graphs, but raw plots such as this show the inhomogeneous nature of the till due to the presence of scattered magnetic rocks and boulders.

("HRAM") of this field and the surrounding area in 1999 located a series of troublesome magnetic anomalies over glacial till that caused problems in the magnetic interpretation (P. Millegan, personal communication, 2003) and were a source of contention between the oil company and the contractor. Interestingly enough, Applied Geophysics, Inc. flew this field in 1985 at approximately 1000 ft (305 m) ground clearance and had no such problems. In fact, in preparing material for this paper in 2002, we attempted to bring out the glacial till anomalies via filtering, without success. The anomalies were so attenuated at the 305 m ground clearance that they were overridden by the response from basement at 1800 m (6000 ft) depth (see comments on attenuation in Conclusions).

Example E5. This example concerns another contentious relationship between a consulting geophysicist and, in this case, a mining company because of the failure to recognize glacial till anomalies. A low-level 1980 Input EM and magnetic survey was flown in the search for zinc deposits in the Rhinelander area of Wisconsin. The magnetic data was interpreted for depth-to-bedrock and yielded values of 30 to 40 m (calculated on the till anomalies) whereas the actual depth to bedrock was on the order of 60 to 120 m, as estimated from the EM data and proven later by drilling.

Example E6. The Ontonagon River valley in the upper Peninsula of Michigan (Fig. 20) is the site of a quite measurable magnetic anomaly that was the reason for a lawsuit some years ago by a geophysical contracting company that failed to recognize the glacial source of the anomaly and a mining company that felt it had been short-changed by an incorrect interpretation.

I have no magnetic data for examples E4, E5, and E6, only anecdotal discussions from reliable geophysicists, but it is tales like these that encouraged the author to prepare this paper with its many examples. If the broad knowledge of glacial till anomalies found in this paper is

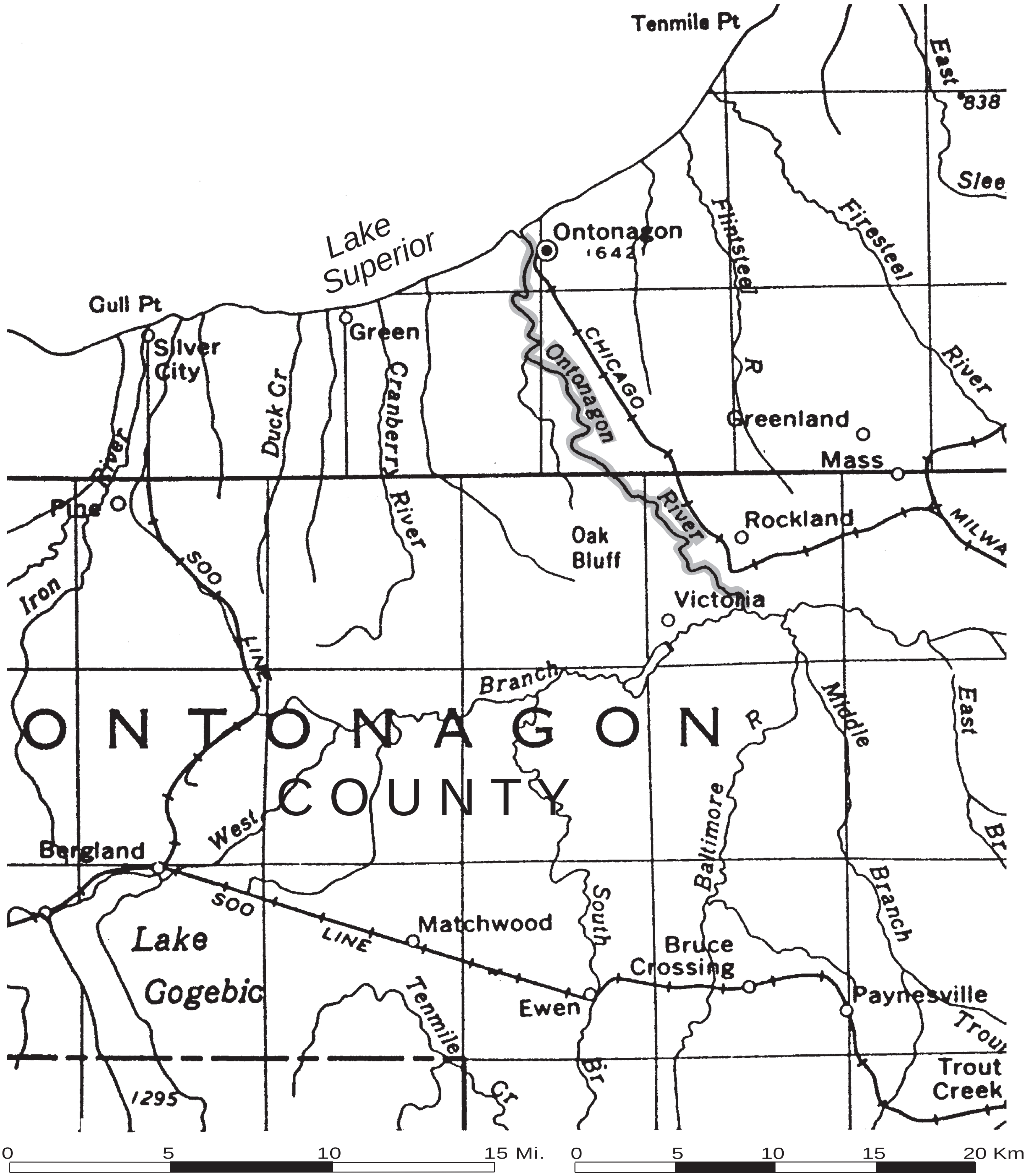


Figure 20. Location map of Ontonagon Valley in upper Peninsula of Michigan. This valley (and probably all the others) is infilled with glacial boulders and is the site of a prominent magnetic anomaly.

widely disseminated within the profession, such anomalies will no longer be a surprise to earth scientists. (Fig. 13, GL3)

Example E7. Minnesota, like Michigan is another state that was overridden multiple times by glaciers, and where the underlying bedrock is sedimentary, rather than igneous or high-grade metamorphic, buried river valleys filled with glacial till are readily mappable with magnetics. Such a situation from a published paper is shown in Figure 21 containing many miles of magnetic river drainages in Carlton County, Minnesota. This example was brought to my attention by former Minnesota state geophysicist, Val Chandler, the author. (Fig. 13, GL3)

Example E8. Dr. Chandler also provided a second Minnesota example from Pine County, this time a graytone image of the 2nd Derivative magnetic map (Fig. 22). Many buried and present-day drainages are readily apparent on this map. (Fig. 13, GL3)

Example E9. Also in Minnesota, in the northern counties of St. Louis and Lake, drumlins in the Toimi area are magnetic and cause measurable anomalies (Fig. 23). This information, without magnetic data, was provided by Rodney Ikola, consulting geophysicist, Hibbing, Minnesota. (See Figs. 33 and 34 for a similar example from Canada.) (Fig. 13, GL1)

Example E10. At the end of a glacial epoch when the glacier-generating weather changes and a continental glacier founders and melts in place ("global warming"), a "knob and kettle" topography results. The kettles form where glacial debris slides off large unmelted blocks of ice and accumulates around the edges. The airphoto in Figure 24 shows such an area in NW North Dakota. A topographic map of a similar nearby area in NE Montana is shown in Figure 25. Many of the kettles contain lakes, others do not. The author ran a ground magnetic profile over two dry kettles in this area in 1990 - Figure 26. Note how the magnetic profile mimics the topography, a result of the magnetic nature of the till. Modelling yielded a figure of 560 x 10^{-6}

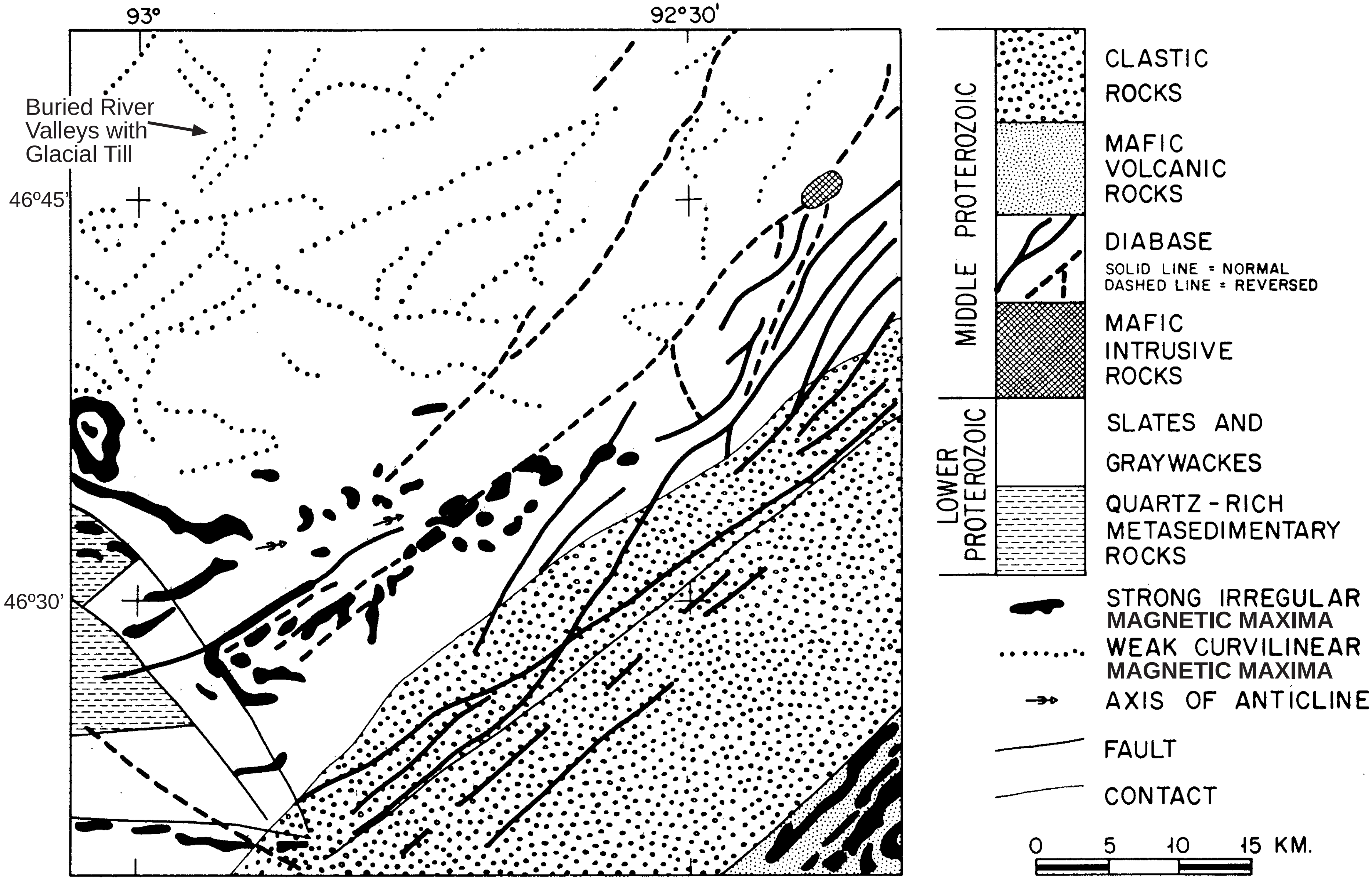


Figure 21. Geology interpreted from airborne magnetic data, Carlton County, Minnesota. Note the many kilometers of river channels infilled with glacial materials, here labeled "weak curvilinear magnetic maxima." From Chandler, 1985.

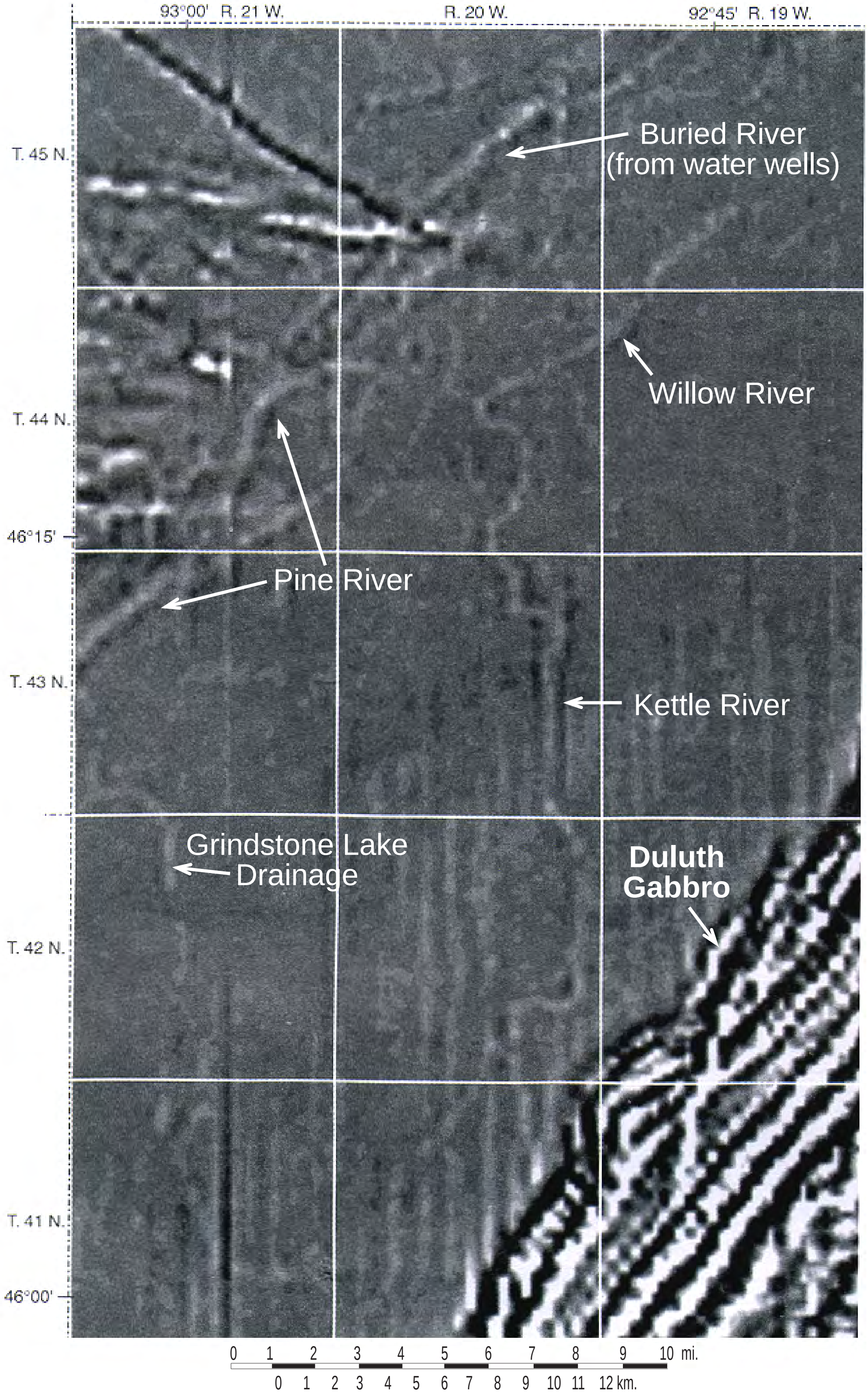


Figure 22. Graytone aeromagnetic map of an area in Pine County, Minnesota, showing numerous magnetic anomalies associated with rivers, both present and abandoned. Map and processing by V. W. Chandler. Published in Boerboom, 2001.

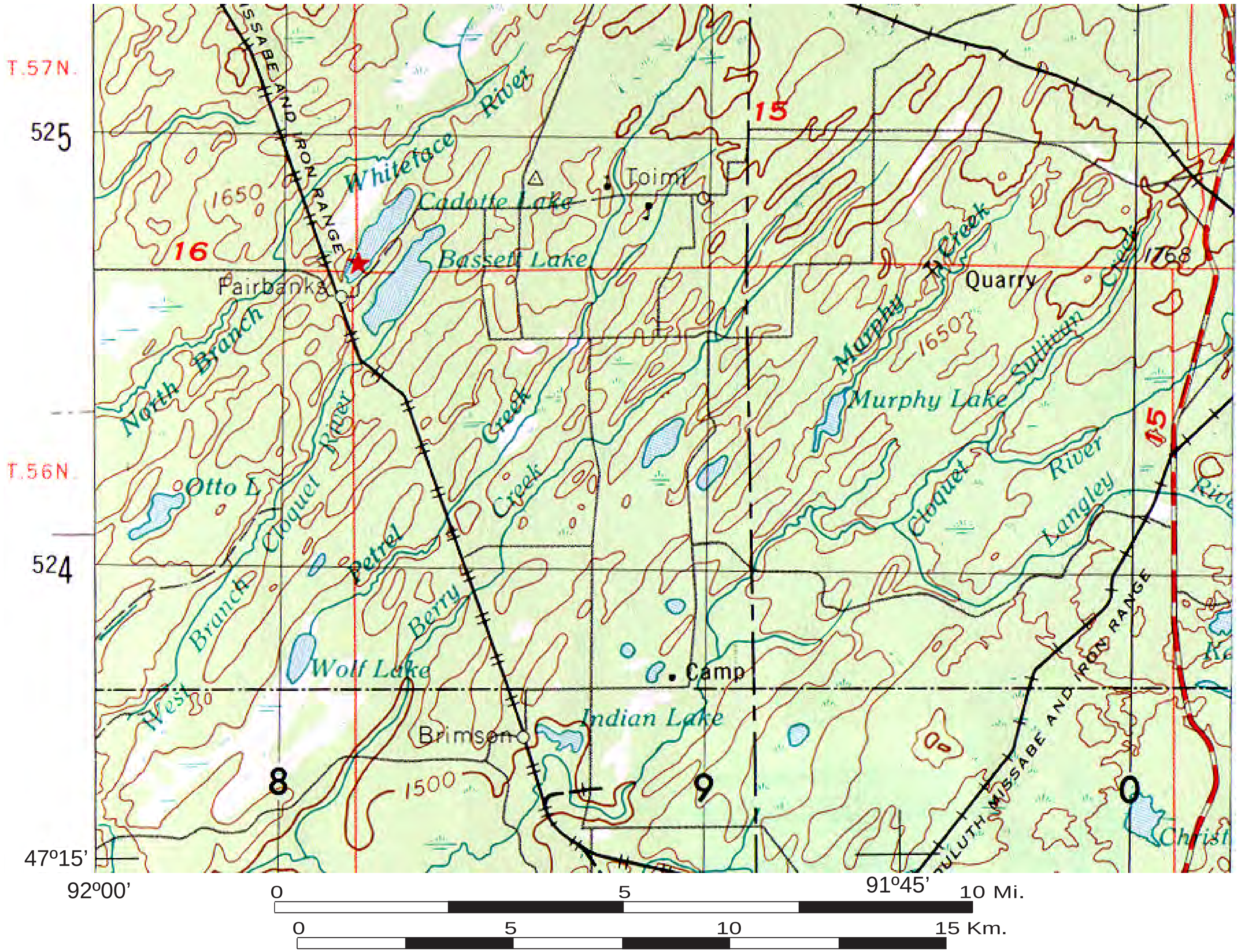


Figure 23. Topographic map of the Toimi drumlin area in St. Louis and Lake Counties, in northern Minnesota. The presence of multiple magnetic anomalies over these drumlins was noted by consulting geophysicist Rodney Ikola, Hibbing, Minnesota (no map was provided).

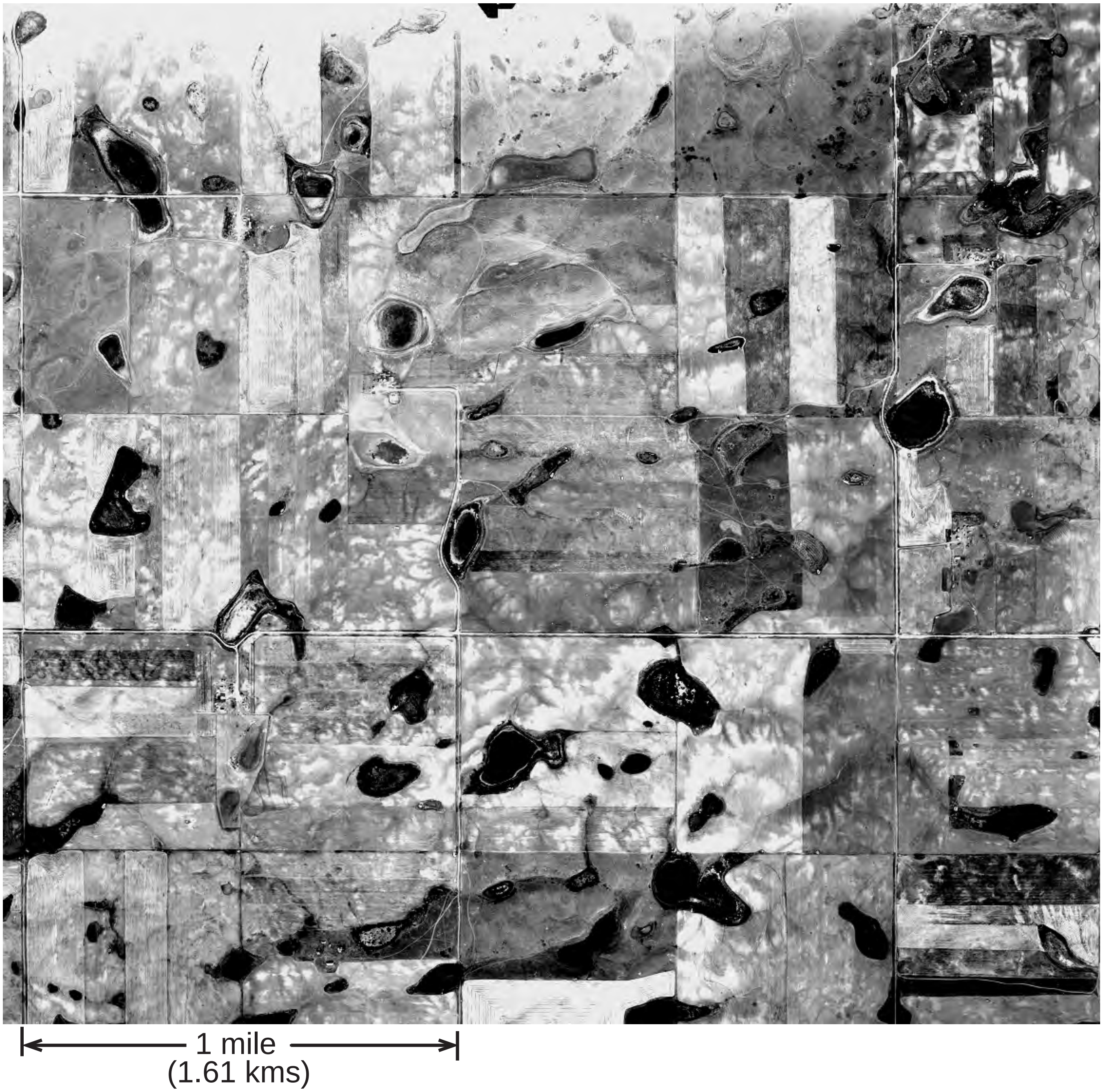


Figure 24. Very illustrative airphoto of glacial "knob and kettle" topography in north central Williams County, in northwest North Dakota. Note that kettles are low, closed drainages often occupied by lakes. They result during the last stages of glacial melting when the sediment atop large blocks of ice slough off the sides, leaving less sediment where the block once sat. This area lies about 75 kms (45 mi.) southeast of area shown in next figure. From Howard, 1960.

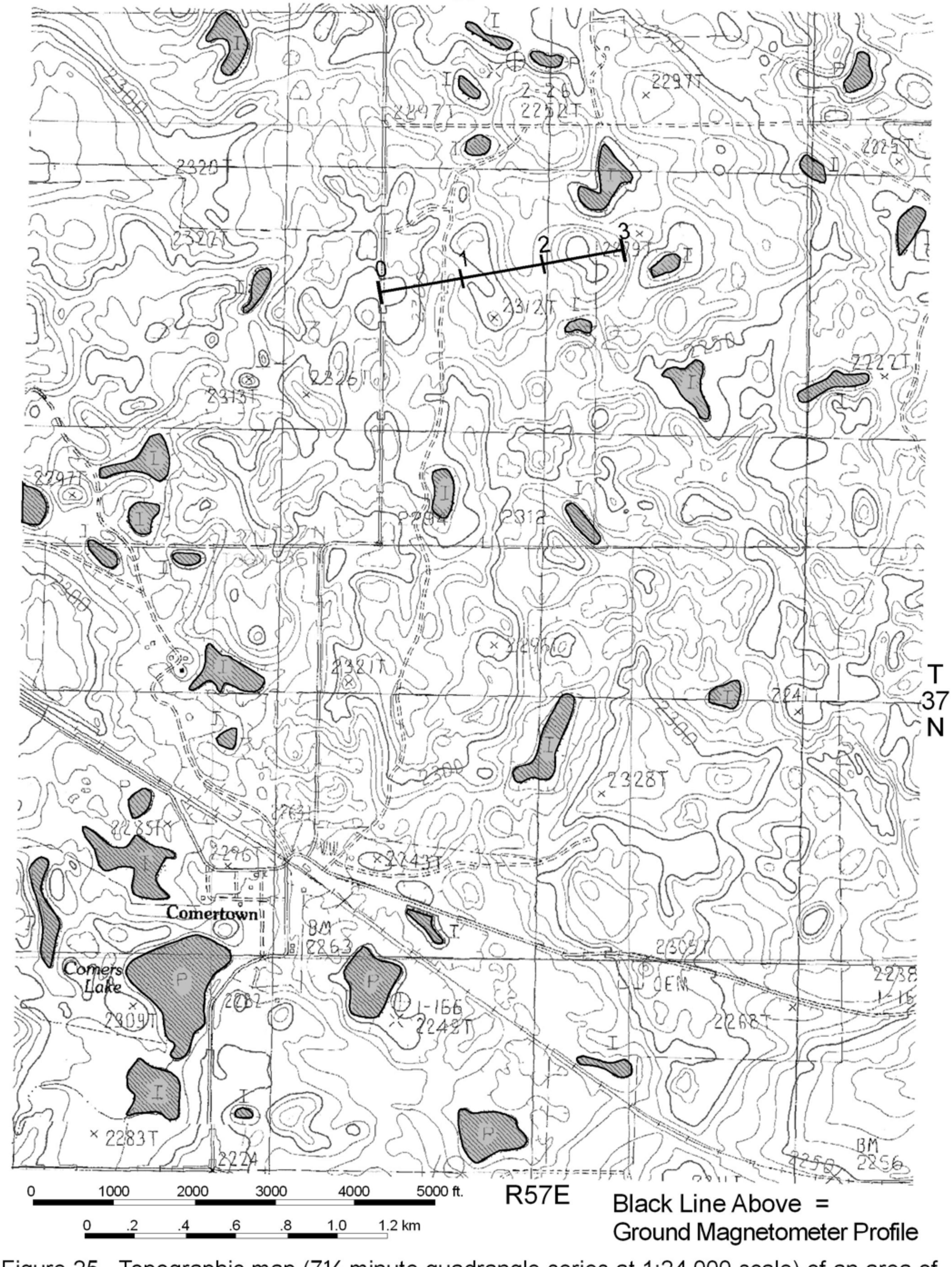


Figure 25. Topographic map (7½ minute quadrangle series at 1:24,000 scale) of an area of "knob and kettle" topography in Sheridan County in NE Montana. Black line is the location of magnetic profile shown in the next figure. Location of this area is shown in Figure 7.

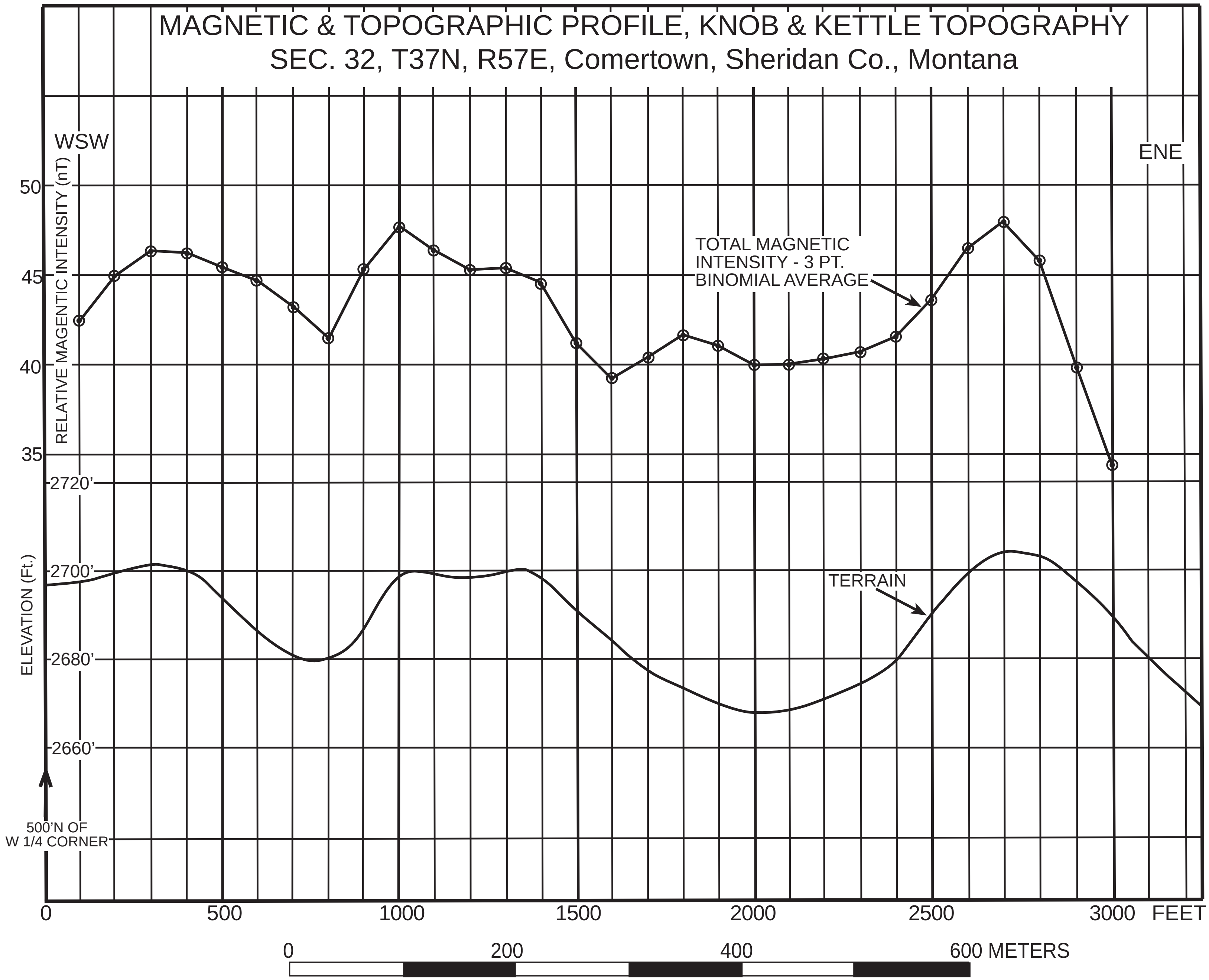


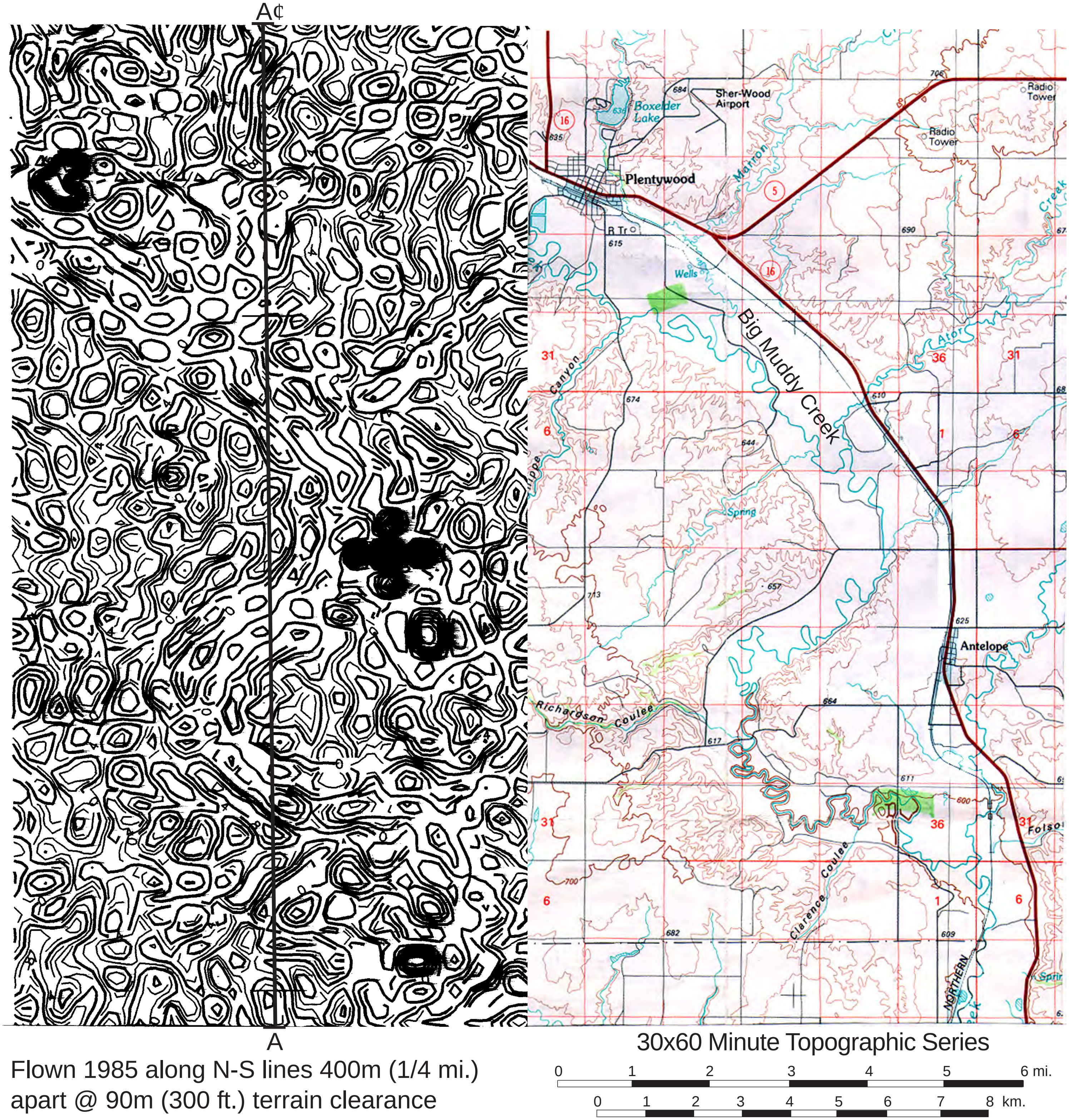
Figure 26. Ground magnetic and topographic profiles of knob and kettle topography falling within glacial till-covered area shown in previous figure. Note how magnetics mimics the topography, proving the magnetic nature of the till. Modelling gave a figure of 560 x 10^{-6} cgs magnetic susceptibility.

c.g.s. average magnetic susceptibility for the till. Note that the magnetic data was smoothed with a 3-point binomial average before plotting, since prior to averaging, the profile was very noisy, similar to the ones shown in Figure 19. (Fig. 13, GL6)

Example E10 cont. Two of the most illustrative examples of the magnetic nature of glacial till appear in Figures 27 and 28. These show different parts of the same area in NE Montana discussed in the previous paragraph. Locations of the figures are plotted in Figure 7, revealing that the surface materials are the early Wisconsin and late Wisconsin (Mankato) drift sheets. There is background magnetic noise due to the glacial till sheet of 1 to 2 nT throughout the areas of Figures 27 and 28 on this data set acquired at 300 ft ground clearance (Fig. 13, GL7). The magnetic profiles in Figure 29 show this background glacial noise very clearly. However, in Figure 27, note the higher, consistent 2 to 4 nT response due to infilled boulders in the 4 to 8 mile wide Big Muddy Creek valley that lies adjacent to the town of Plentywood, Montana. In Figure 28, we see the same type of magnetic response in two areas not coincident with rivers. Here, there are obviously ancient drainages buried by younger drift. (Fig. 13, GL3, GL5)

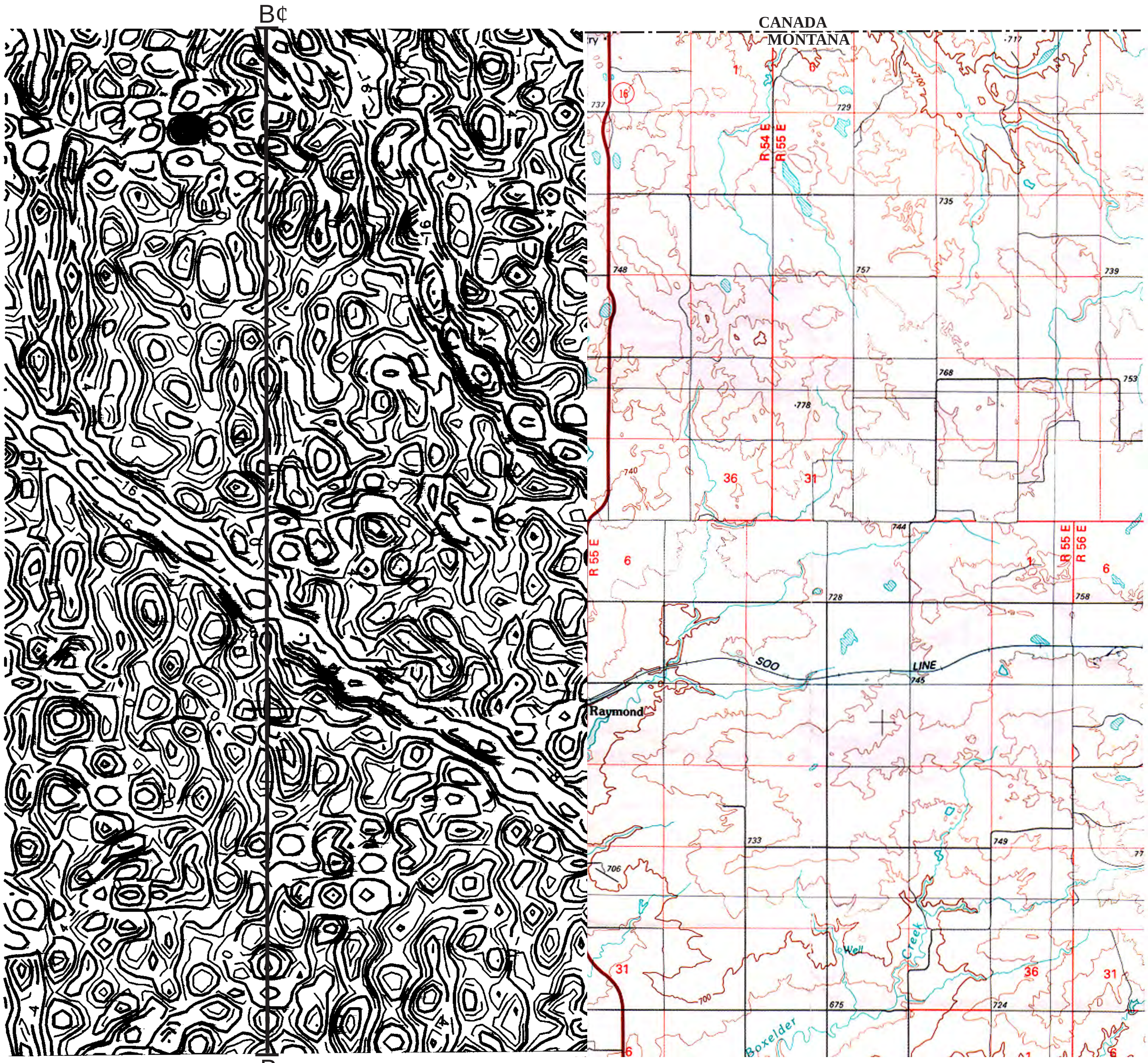
Due to the high background glacial noise in the magnetic data this area would clearly not lend itself to the search for low-amplitude, high-frequency magnetic anomalies of the type ascribed to alteration chimneys over oil and gas fields, although it was tried in the 1980's. In that case, an additional problem arose - the misidentification of anomalies over 30 ft x 30 ft steel grain bins (in various numbers from 1 to 10 or more in a group) as possible alteration chimneys (see Fig. 30).

Example E11. An interesting example of magnetic anomalies over lateral moraines from a mountain glacier are shown in Figure 31. This unpublished example is from the north flank of the Beartooth Mountains in Montana and was provided by independent mining geophysicist



Flown 1985 along N-S lines 400m (1/4 mi.) apart @ 90m (300 ft.) terrain clearance Applied Geophysics reprocessing.

Figure 27. Short wavelength 2nd derivative magnetic contour map over the Early Wisconsin drift sheet in the Plentywood area of NE Montana. Location of area is shown in Figure 7. Note the persistent magnetic high over the drainage valley of Big Muddy Creek due to deeper glacial till here, undoubtedly an infilling of reworked glacial boulders. See magnetic profile A-A' in Fig. 29. Thanks to Richard Hansen, of Pearson, deRidder, and Johnson, Denver, for the release of this data.



30x60 Minute Topographic Series

0 1 2 3 4 5 6 mi.

0 1 2 3 4 5 6 7 8 km.

Flown 1985 along N-S lines 400m (1/4 mi.) apart @ 90m (300 ft.) terrain clearance Applied Geophysics reprocessing.

Figure 28. Short wavelength 2nd derivative magnetic contour map of an area covered by Mankato drift on the Canadian border north of that shown in the previous figure. A long linear magnetic anomaly similar to the one over Big Muddy Creek occurs in a topographically flat, featureless area, indicating a buried river channel. See magnetic profile B-B' Fig. 29. Another channel, part of an oxbow, appears in the upper right quadrant. Thanks to Richard Hansen, of Pearson, deRidder, and Johnson, Denver, for the release of this data.

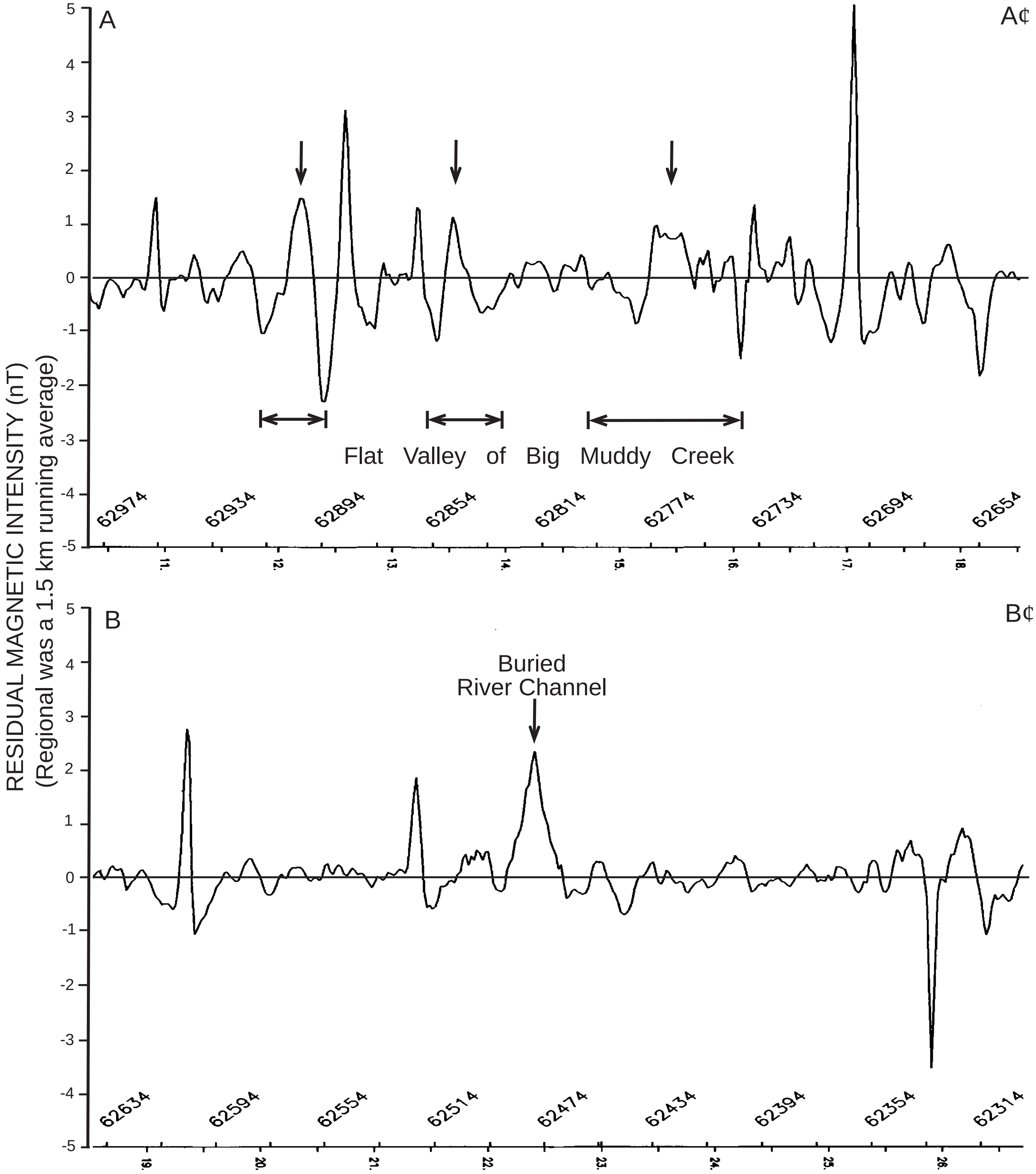


Figure 29. Magnetic profiles from flight line data (Line 16) for lines indicated in previous two figures. On profile A-A' (Fig. 27) note the locations of the three crossings of Big Muddy Creek Valley and the 2-4 nT magnetic highs that correspond to them. On profile B-B' (Fig. 28) note the 3 nT high over the prominent NW-SE trending buried river channel. Sharp spikes that have amplitudes of 3 to 5 nT or more are, in most cases, cultural, mainly grain bins. Background 1-2 nT anomalies evidently arise from variations in thickness and susceptibility of the pervasive glacial till sheet. System noise was less than 0.30 nT.

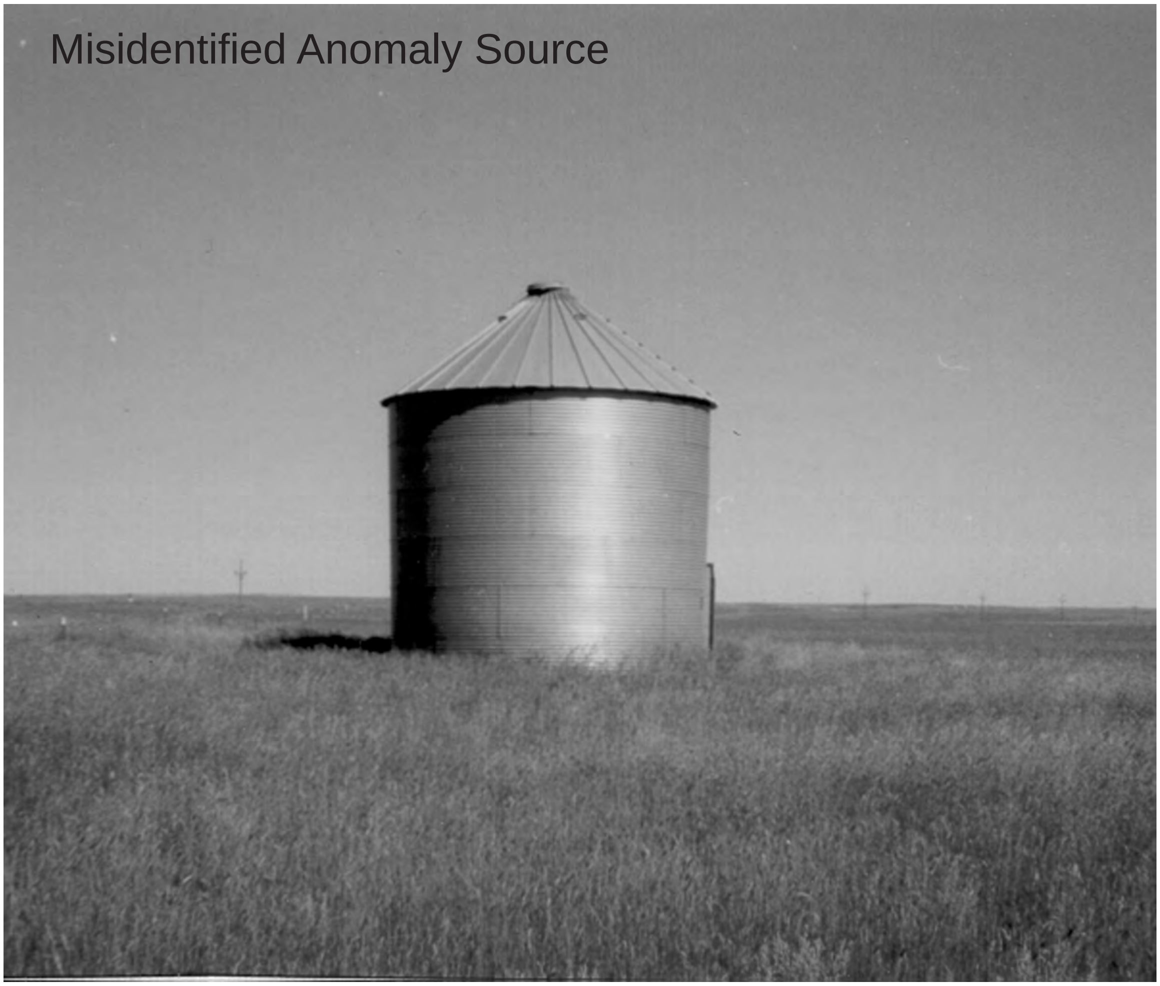


Figure 30. A galvanized steel grain bin of the type identified (1989) as the cause of a "NSMA" (near-surface magnetic anomaly), which is correct, but these anomalies were presumed to be candidates for alteration chimneys over oil and gas fields, Sheridan County, Montana. Photo by the author.

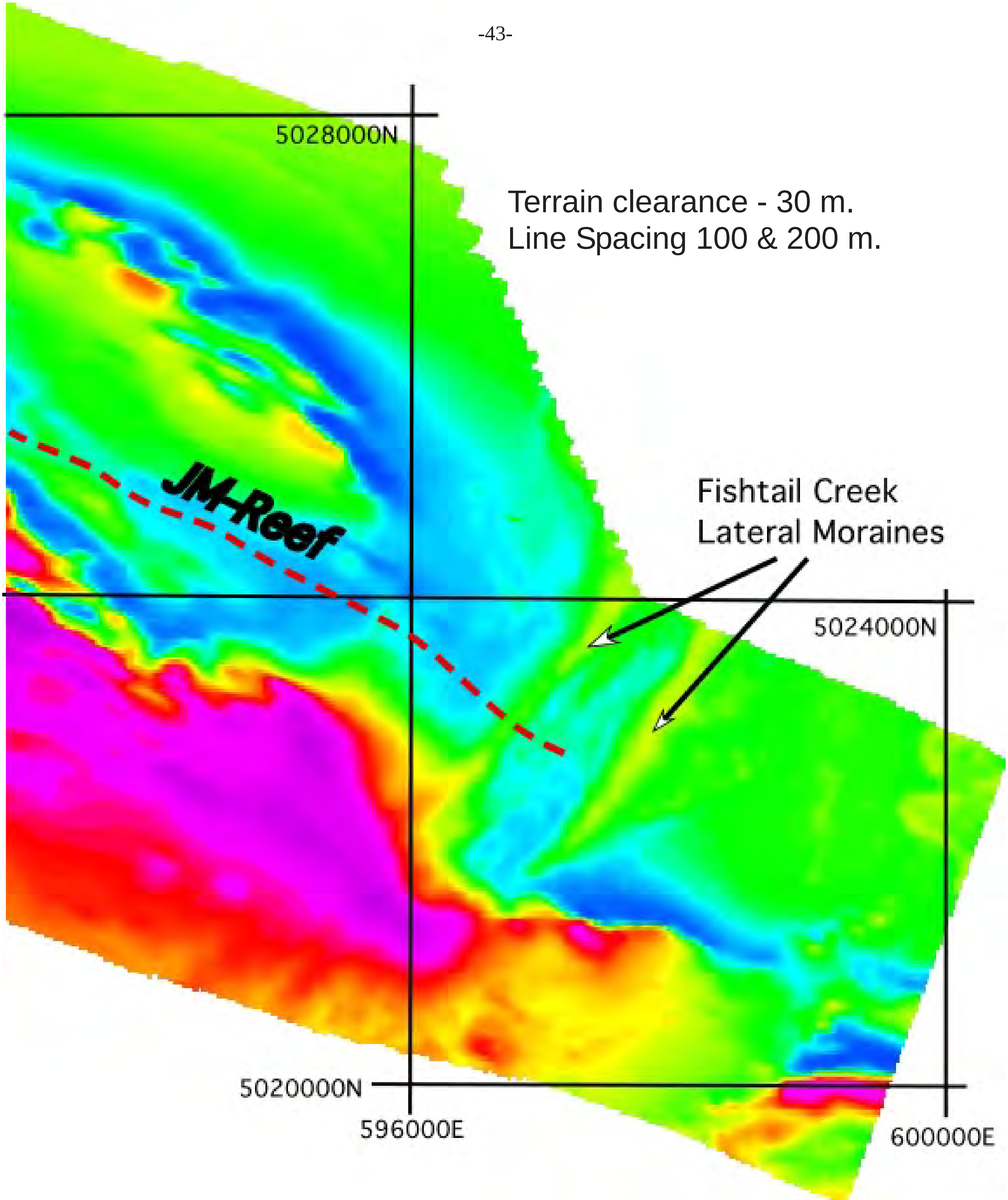


Figure 31. Total intensity helicopter magnetic map on the NE flank of the Beartooth Mtns., Montana, over Stillwater ultramafic complex. From Terry Crebs, independent geophysicist, Denver, CO.

Terry Crebs of Denver, Colorado, discoverer of the Voisey's Bay nickel deposit in Labrador. (Fig. 13, GL1)

Example E12. I now turn my attention to Canada and will show a number of examples in this large country that is almost completely covered by glacial till. Starting on the east in northern Ontario, geophysicists R.L.S. (Scott) Hogg and S. S. Munro in an article on their website entitled: "The aeromagnetic discovery of kimberlites and sulphides at depths up to 200 m," state: "The glacial till ... can also contain magnetic material and can produce a ... measurable response. It is suspected that some karsts have been filled with glacial gravels and ... in such cases cause significant anomalies." (See Fig. 32 for location.)

Example E13. Hogg also provided another extremely illustrative example from farther east in Ontario just south of James Bay. These are low-level stacked magnetic profiles (Fig. 33) across a wide river that shows lows of up to 20 nT amplitude coincident with the river. This would correspond to the writer's example GL4 in Figure 13, glacial till removed from a till sheet by the action of rivers.

Example E14. Another interesting example, this one from northern Saskatchewan, is shown in Figure 34. A very busy residual magnetic map from a Geological Survey of Canada (GSC) bulletin shows dozens of parallel magnetic highs completely blanketing a 17x17 km segment of the Athabaska Test Area (Kornic, 1983). This example was brought to my attention by GSC geophysicist Peter Hood. How could an area be so pervasively covered with parallel glacial till anomalies? That is explained by another GSC product, an airphoto (Fig. 35) captioned "vertical photo of a drumlinized and grooved glacial plain," that appeared in Thornbury's text, "Principles of Geomorphology" (1966, p. 365). (Fig. 13, GL3)

Example E15. In NW Alberta, an HRAM ("high resolution aeromagnetic") survey in the

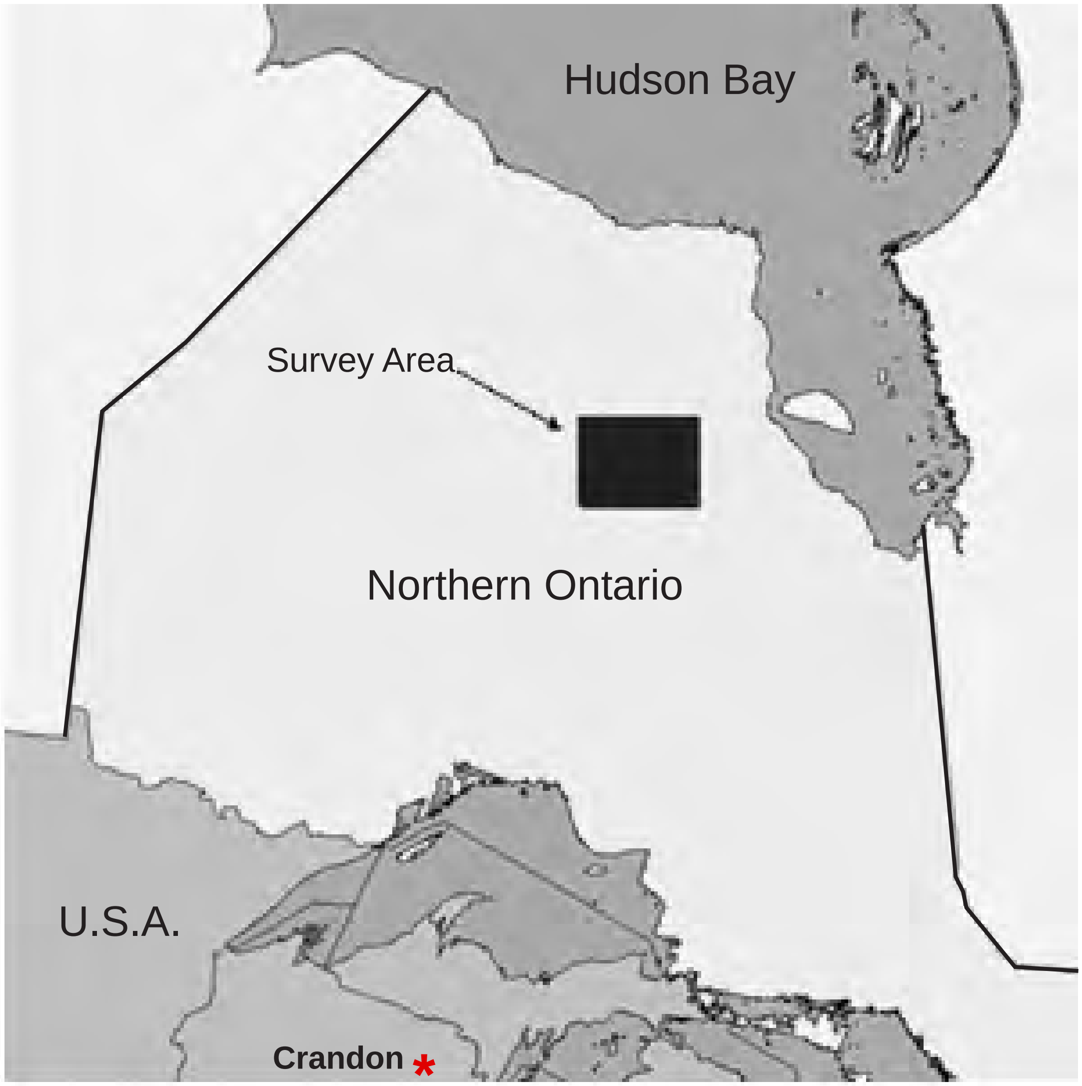


Figure 32. Location map for an internet article: "The aeromagnetic discovery of kimberlites and sulphides at depths up to 200 m," by R. L. S. Hogg and S. S. Munro.

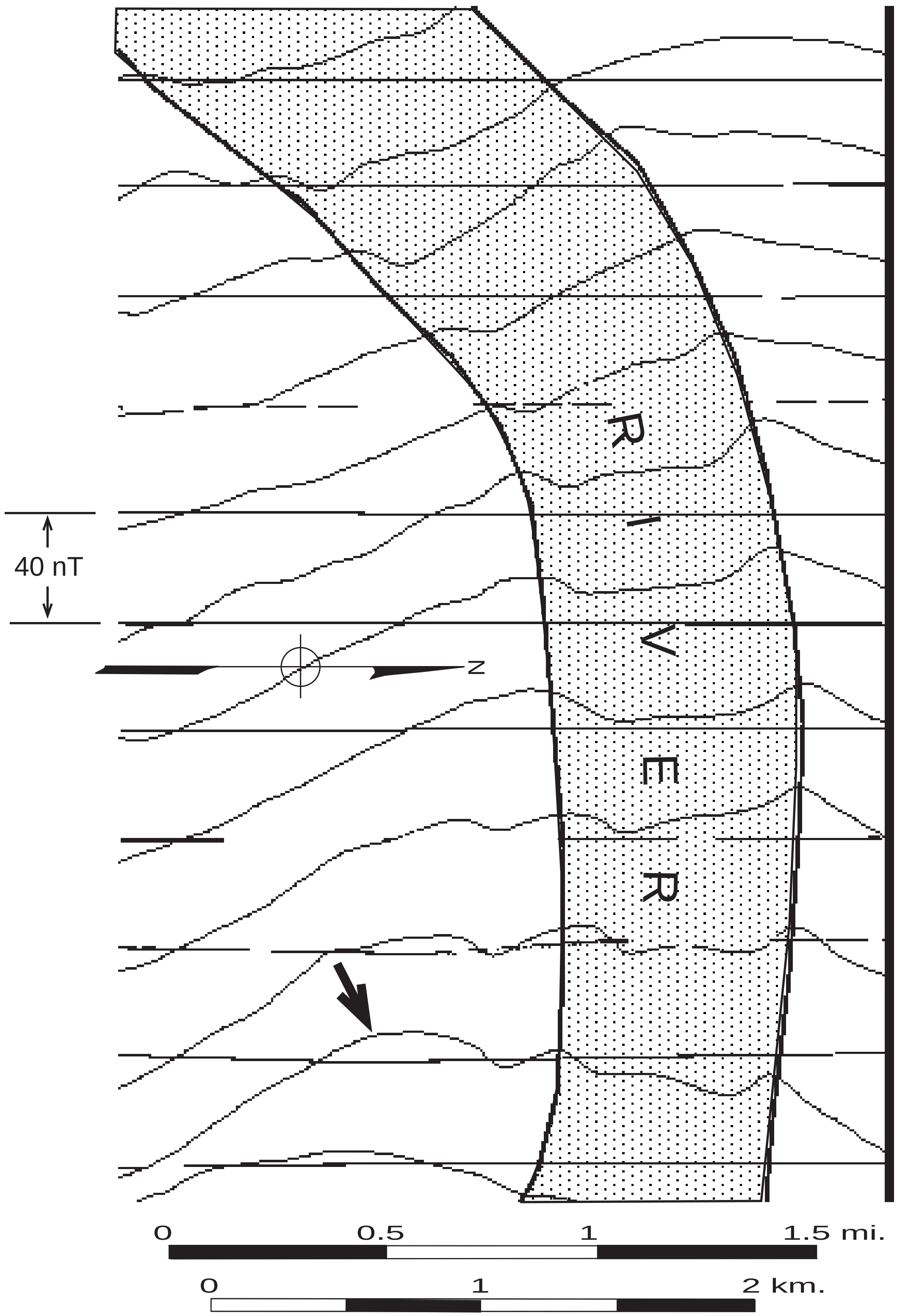


Figure 33. Stacked aeromagnetic profiles over river carved in glacial till, James Bay lowlands, Ontario, Canada. Data from Scott Hogg, consulting geophysicist, Toronto, Canada.

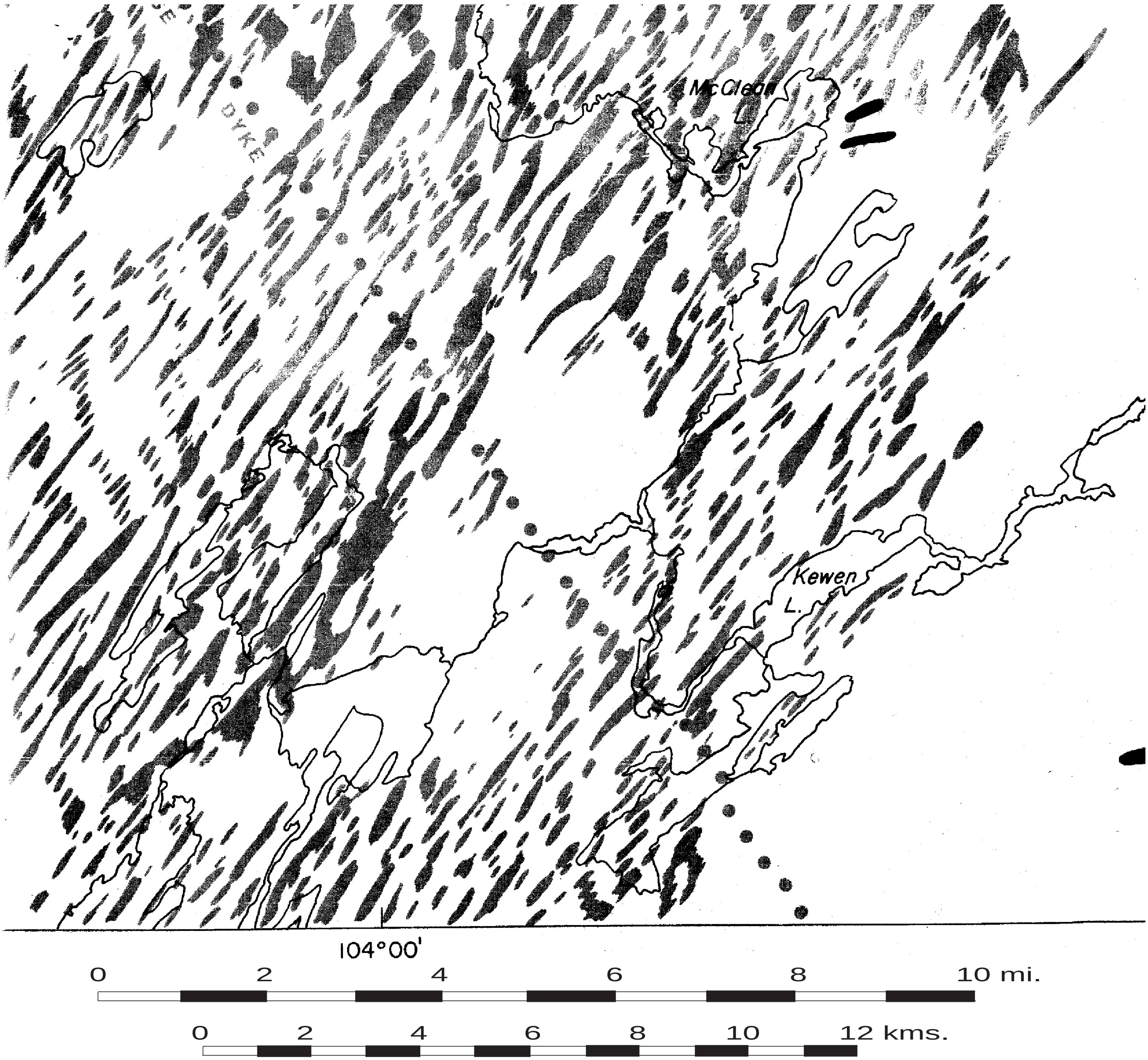


Figure 34. A very busy aeromagnetic map of short wavelength (i.e. narrow) anomalies from glacial deposits in the NEA/IAEA Athabasca test area, Saskatchewan. From Kornic, 1983.

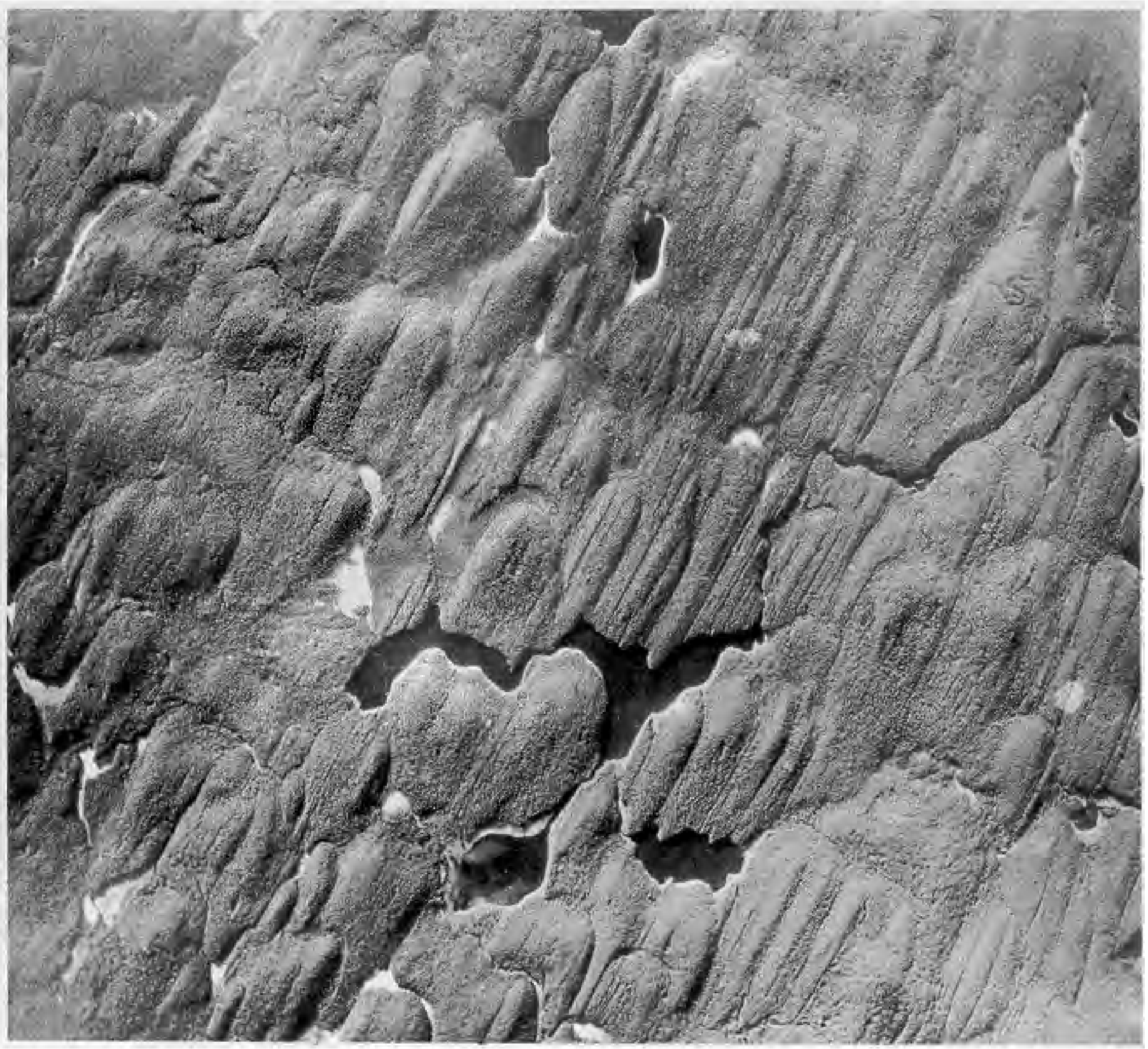


Figure 35. Airphoto of a "drumlinized area" in Canada. The magnetic map of Figure 34 would have been flown over such an area. From Thornbury, 1966 (no location given).

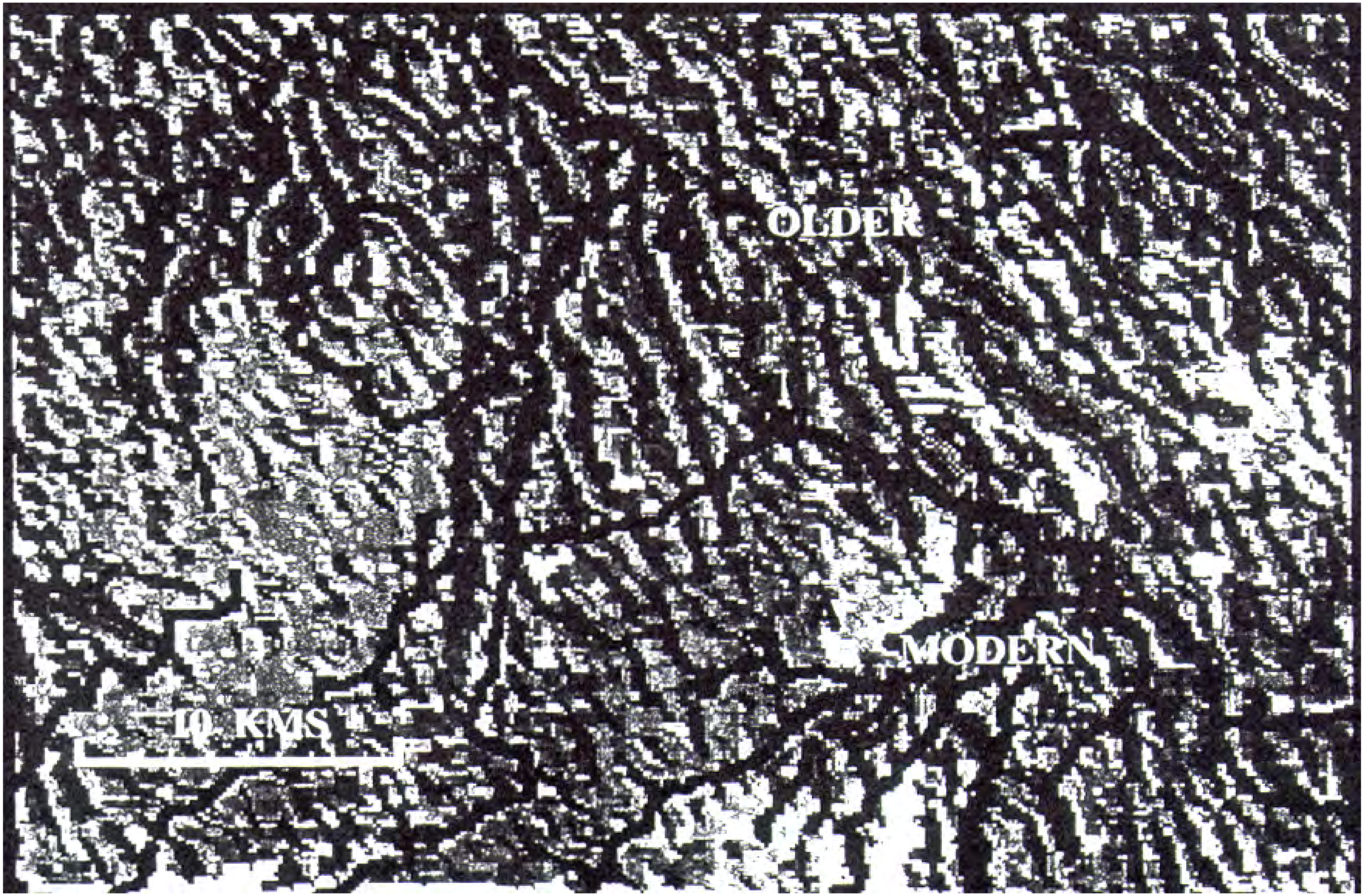


Figure 36. Shallow "depth slice" of HRAM data, Zama Lake area, NW Alberta, Canada. From Glenn, et al, 1997. This display, and its contained drainages, is similar to that from Minnesota shown in Figure 22 and others in this paper, and undoubtedly results from the same cause - glacially infilled valleys.

glacial covered Zama Lake area (Glenn, et al, 1997) was processed for near-surface effects ("depth slice 1") and yielded the results shown in Figure 36. Although the drainage pattern shown here was attributed to channels carved into the magnetic(?) Cretaceous Bad Heart formation, its similarity to the drainages infilled with glacial materials shown elsewhere in this paper make it more likely that these are glacial channels. Clearly, field checking and ground magnetic surveying in this area are in order.

(Fig.13, GL3)

Starting in the early 1990's and continuing to the present time, an exploration boom of unprecedented proportions for diamonds has taken place in Canada. The lead geophysical tool for this exploration is low-level, tightly spaced, electromagnetic (EM) and magnetic flying, much of it with helicopters. The most successful exploration has been carried out in the Northwest Territories where diamond-bearing kimberlite pipes of Precambrian age were intruded into igneous/metamorphic Precambrian host rocks. Two high-grade deposits, Ekati and Diavik, have already been put into production, and others will soon follow. Glacial till magnetic anomalies are certainly present, but in this hardrock environment the till anomalies are <u>overridden</u> by the response from the underlying igneous/metamorphic hosts.

Example E16. Some of the Canadian diamond exploration has been carried out farther south in the province of Alberta, however, where Cretaceous-age kimberlite pipes intrude the sedimentary section of the Western Canada Basin. Here, the glacial till magnetic anomalies are readily visible on the low-level, tightly-spaced surveys. In fact, one operator drilled "many" such magnetic targets in the Peace River area of NW Alberta without finding kimberlite (Tony Rich, New Claymore, Ltd, personal communication, 2003). (Fig. 13, GL2 or 3)

Example E17. Another operator, had a similar experience in the Birch Mountain area of NE Alberta. Shear Minerals in their 2001 annual report stated: "Geophysics was conducted on nine targets, three of which were prioritized for drill testing. No kimberlites were intersected and the cause of the anomalies was interpreted as magnetic material in glacial till." This example was provided by Keith Jones, consulting geophysicist, Perth, Australia. (Fig. 13, GL2 or 3)

Example E18. Likewise, Montello Resources, Ltd, in report MIN 19990005 submitted to the Alberta Geological Survey, 2000, describing their exploration work in the Muskwa and Teepee Lakes area of N. Central Alberta, stated:

> "The work consists of 24,430 line kilometers of airborne magnetometer surveys. The parameters used were tie-lines at intervals of 1 km N-S and survey lines at intervals of 200 m E-W ... The results are proffered on 4 maps each for [total intensity and vertical gradient] at a scale of 1:50 K and 2 nT contours. A number of anomalies were selected from the airborne magnetic survey, and a ground magnetics survey was conducted totalling 1,046 line kilometers. Seven anomalies defined from ground magnetics were drilled in an attempt to find kimberlites. Seven holes were drilled for a total of 949 meters. After the ground magnetics were about half completed, and reviews and manipulation of airborne data and four holes drilled, it was clear that some or **probably most** of the airborne magnetic anomalies stemmed from sources within the glacial debris (drift) section."

This example was also provided by Keith Jones, geophysicist, Perth, Australia. (Fig. 13, GL2 or 3)

Example E19. Certainly, many more such examples of glacial till anomalies from the diamond exploration community could be uncovered in Alberta and perhaps other places as well, but I end this section with Figure 37. This shows 4 magnetic anomalies - 3 helicopter-borne and one ground magnetic survey - that were drilled for kimberlites in the Buffalo Head Hills area of NW Alberta, but were all found to result from (reworked) glacial till. (Fig. 13, GL2 or 3)

These last examples (E16-E19) from the diamond exploration industry are a good indication of the pervasiveness of glacial till in Alberta. I do not mean to infer that all magnetic targets in Alberta result from glacial till, as several dozen kimberlite bodies have been found in

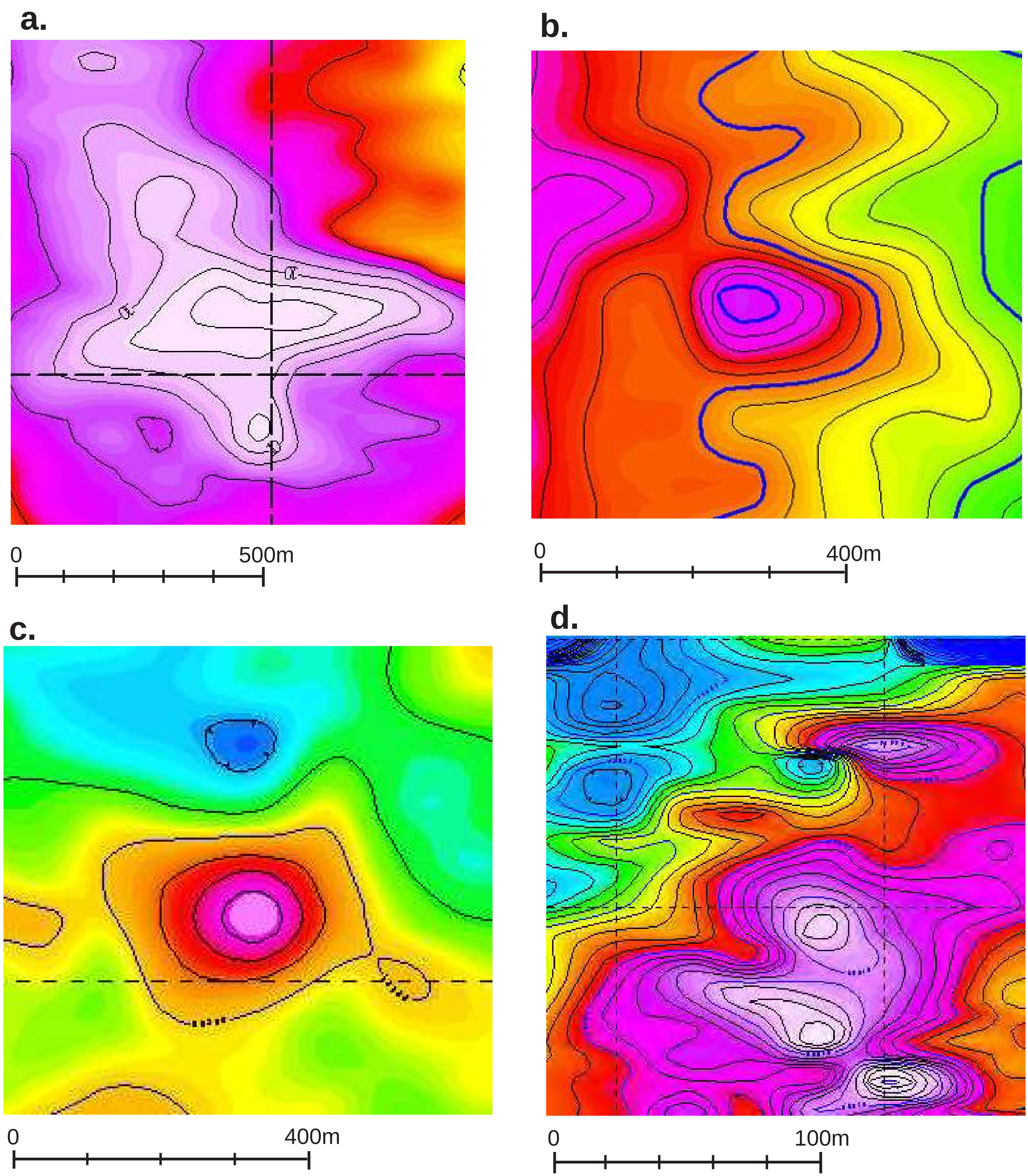


Figure 37. Magnetic anomalies from the Buffalo Head Hills area in northwest Alberta that were targets for kimberlite (diamond) pipes but, upon being drilled, were found to be caused by glacial boulders. Anomalies **a**, **b**, and **c** are helicopter-borne HRAM surveys, line spacing 50 m, sensor height 40 m. Map **d** is a ground magnetic survey. All maps 2 nT contour interval, north is up. This material was brought to the writer's attention by geophysicist Keith Jones, and the data were provided by geophysicist Dave Skelton, Ashton Mining, Ltd., Vancouver, B.C., Canada.

the province. But there has certainly been a problem of separating "good" anomalies from "bad" anomalies, and the way it's been done so far has been with the drill - a very expensive procedure. (Probably ground EM, resistivity, and/or induced polarization methods could be used to screen the many airborne magnetic anomalies that this intensive survey effort has produced.)

Example E20. In the southern part of the Alberta Basin adjacent to the U.S. border, Leblanc and Morris (1997) describe glacial till anomalies without recognizing their cause. They state: "This data set contains four distinct magnetic textures ... [including] c) high-frequency low-amplitude curvilinear features ... [that]...partially follow along river systems," and they add: "Some river gravels [sic] are known to have a weak magnetic signature associated with them." The many examples of anomalies coincident with rivers or drainages that result from post-glacial reworked tills, especially Figures 15, 18, 20, 21, 22, 27, 28, 40, and 41 that appear in this paper, leave little doubt as to the cause of these ..."curvilinear features [that]... partially follow along river systems." (Fig. 13, GL3)

Example E21. Another example of glacial till anomalies from the northern Alberta Basin in NE British Columbia was discussed by Thurston, et al, 1997. They state: "The problem of separating magnetic responses from the Archean and ...[Proterozoic rocks] ... is complicated by the presence of a surficial magnetic layer ... glacial deposits [that] have wavelengths on the order of 200 m ..." There was no figure accompanying this abstract, but their identification of glacial till anomalies is clear. (Fig. 13, GL7)

Example E22. I will now move to Alaska where glacial effects are numerous but have not previously been published or documented, to the writer's knowledge. The late Robert Schnepfe (1933-1991), an outstanding mining geophysicist with Phelps Dodge Corp., who expressed an interest in being a co-author of this paper when the writer first proposed it in 1990, furnished the example shown in Figure 38 from a survey carried out in 1969. There is a low 12 ft (3.6 m) hill of moraine from a mountain glacier in the Yakutat/Nunatak area of SE Alaska that results in a magnetic anomaly of 250 nT. Such a high response from a thin deposit indicates a high magnetic susceptibility for the till, probably resulting from the presence of mafic igneous rocks, such as gabbros, contained therein. Gabbroic intrusive masses are common in SE Alaska and would have been present in the mountain valley from which this glacier issued. (Fig. 13, GL1)

Examples E23 and E24. Two recent Alaskan examples were furnished by John Cady, consulting geophysicist of Golden, Colorado. Figure 39 shows 3 magnetic highs over inferred glacial moraines in the Gagaryah Valley, and Figure 40 shows glacial drainages similar to the others in this paper from the Holitna area of Alaska. The latter figure is perhaps the most illustrative of all the examples in this paper over glacially infilled river drainages, and illustrates the power of properly processed and displayed magnetic data. (Fig. 13, GL3)

Example E25. A most remarkable example of glacial till anomalies was provided by Fugro Airborne Surveys' geophysicist Jeff Rowe. This example is from <u>under</u> the present North Sea, offshore the United Kingdom, and shows fluvially-reworked glacial drainages. During the last glacial epoch sea level was some 100 m lower than at present due to the extensive icecaps that formed on the continents, and this part of the North Sea was obviously above sea level at the time. Figure 41 shows the drainages in plan view, and Figure 42 shows an observed magnetic profile with the modelled profile calculated from the causative source bodies. Arrows point to the moraine or boulder-filled channels. (Fig. 13, GL3)

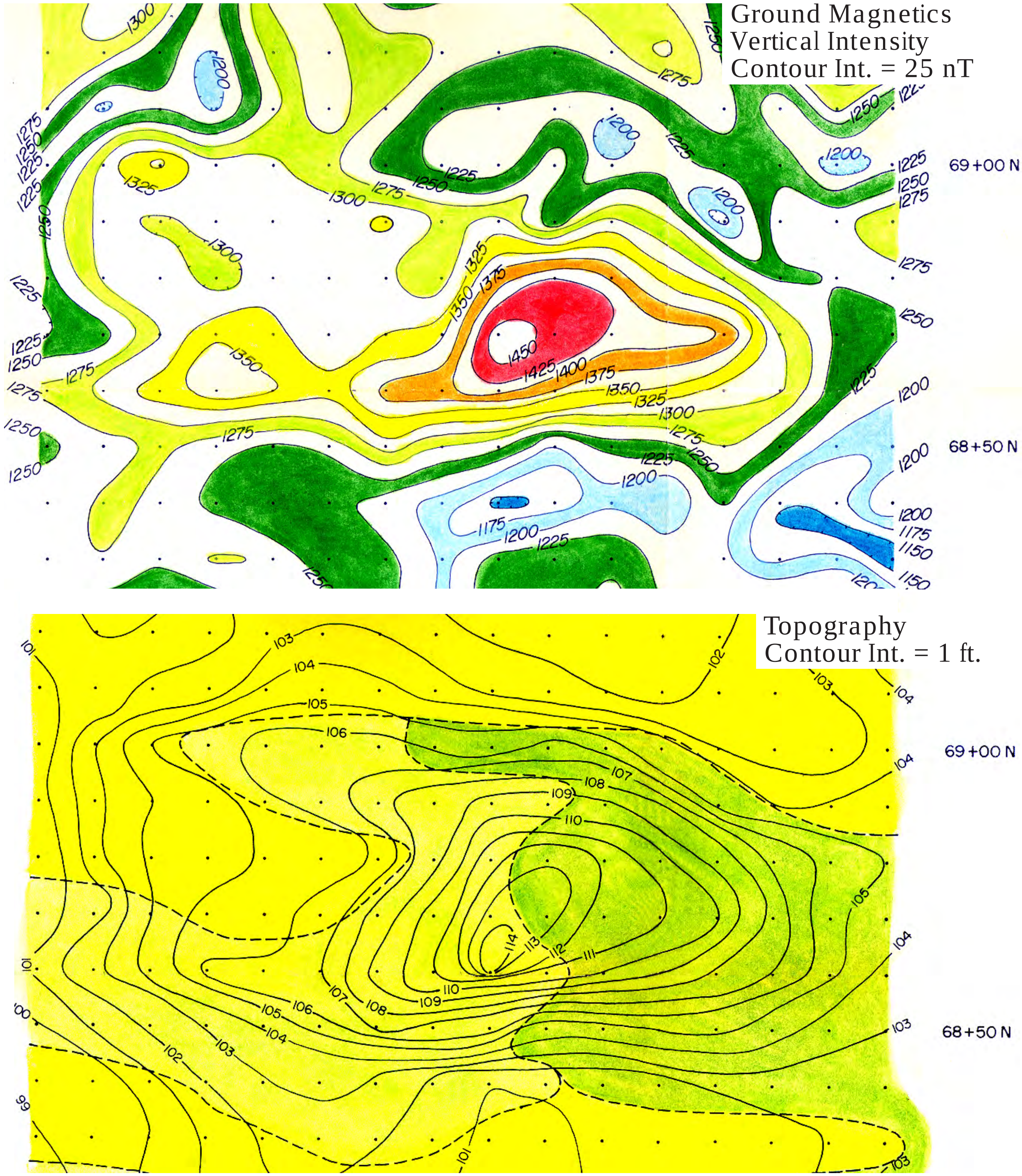


Figure 38. Ground magnetic and topographic contours of glacial till from a mountain glacier in the Yakutat area of SE Alaska. This 12 ft high hill has a magnetic response of 250 nT. Example provided by R. N. Schnepfe (1990).

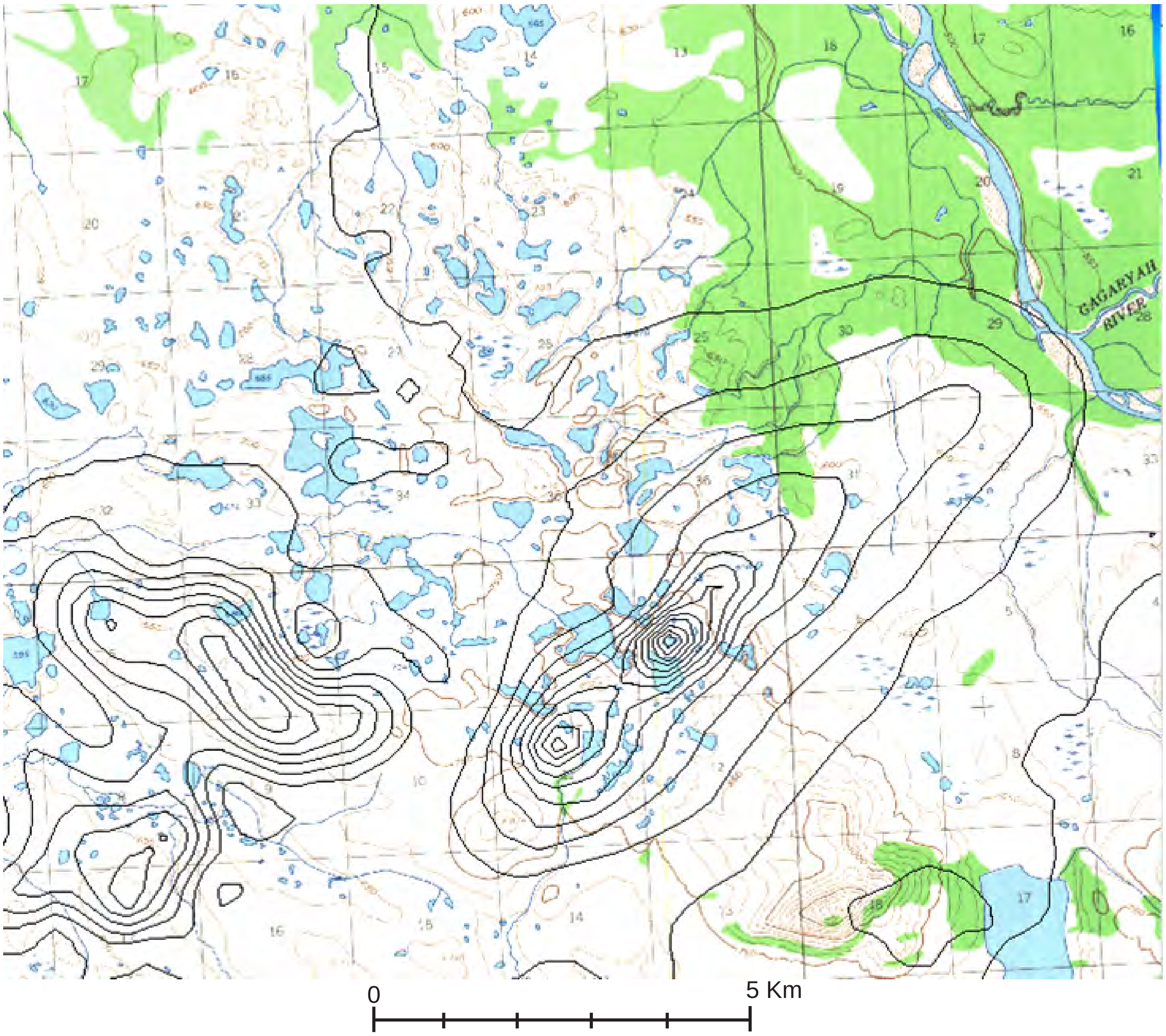
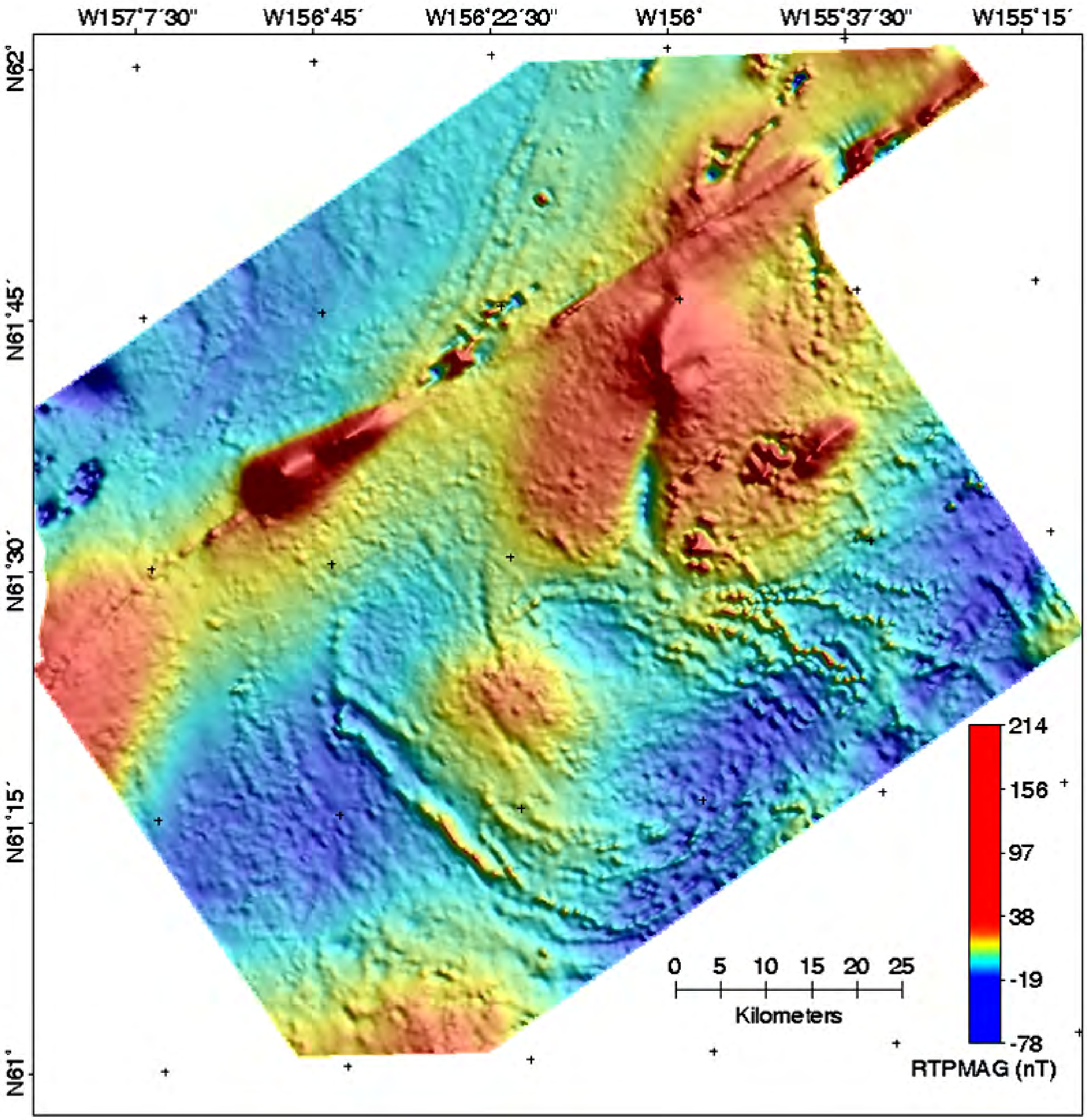


Figure 39. The three 50 to 120 nT magnetic anomalies on this map result from glacial till filling inferred valleys under Gagaryah Valley in Alaska. 10 nT contour interval. Example from John Cady, Golden, Colorado, 2002.



Shade Relief magnetics illuminated from NE

Figure 40. This shade relief residual magnetic map shows a series of river drainages infilled with glacial moraine or reworked glacial boulders in the Holitna area of Alaska. Example from John Cady, Golden, Colorado, 2002.

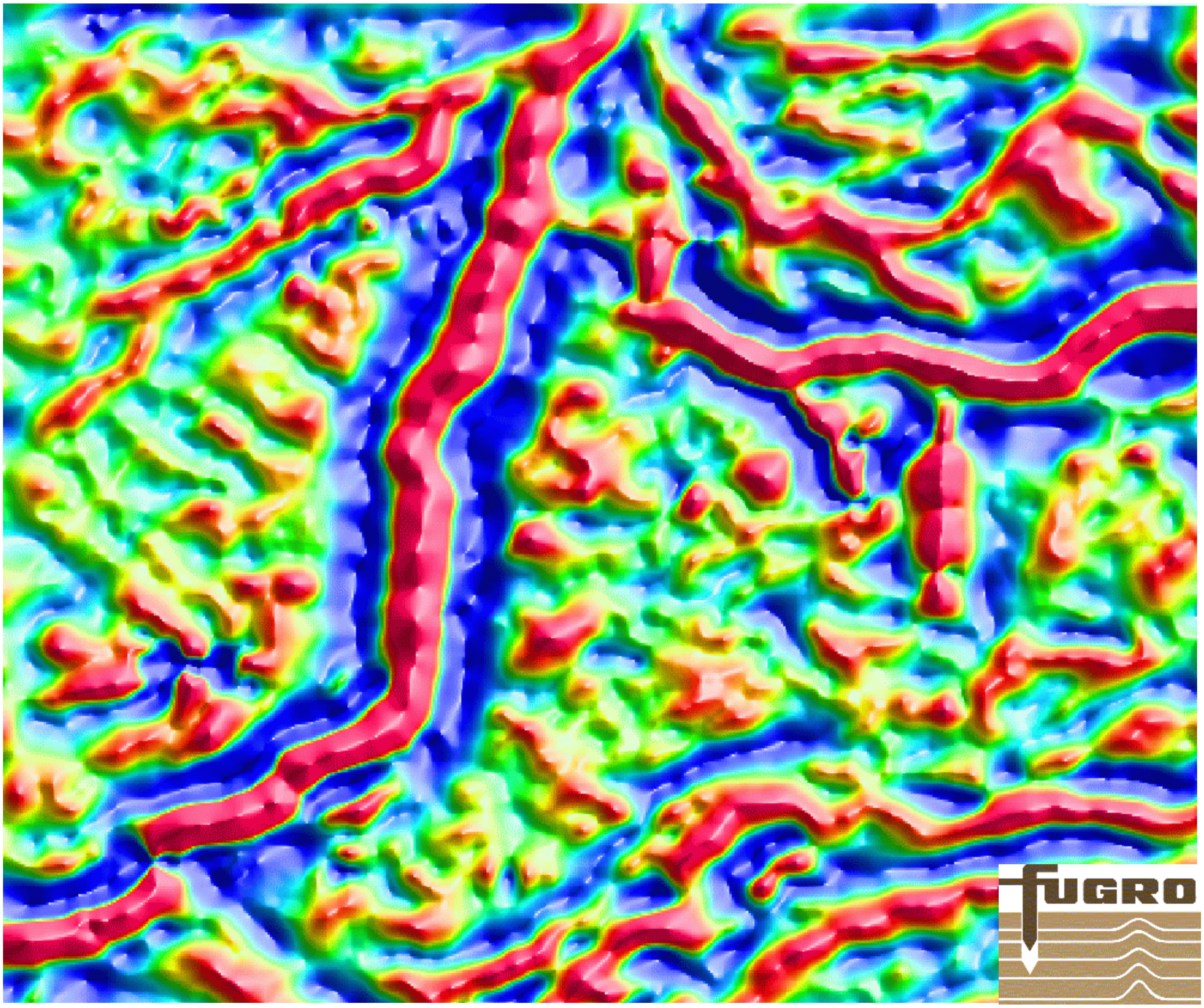


Figure 41. High-frequency residual magnetic map of an area in the North Sea showing a drainage system infilled with glacial materials. Data provided by Jeff Rowe, Fugro Airborne Surveys, 2002.

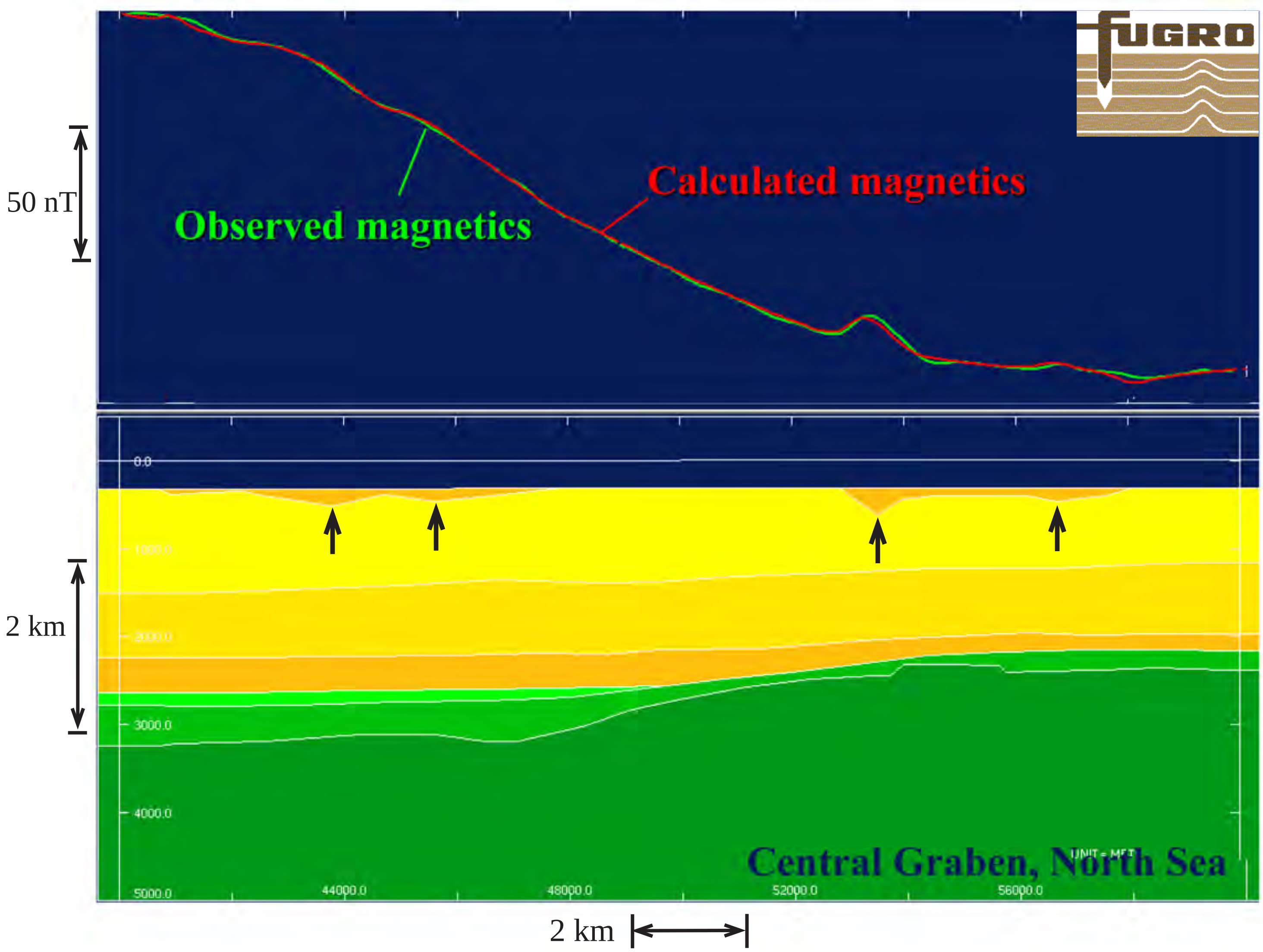


Figure 42. Profiles of observed and calculated magnetics and the subsurface from the survey of the North Sea shown in previous figure. Note the interpreted glacial channels (arrows) carved into what is now the sea bottom, but was once dry land during the Pleistocene epoch. Modelling by Fugro - LCT.

CONCLUSIONS

The foregoing tutorial on glaciation and the many examples of magnetic anomalies over glacial till I show should be of interest to the present-day potential field community, many of whom seem to be unaware of the widespread occurrence of till and of its deleterious effects on magnetic surveys. The problem is particularly acute at the present time when petroleum exploration personnel are being told to fly aeromagnetic surveys "low and tight," which ensures that the maximum amount of spurious glacial till signal will be present in their data. In 1964, the advice given to the potential field community by Michael Reford, then chief geophysicist of Geoterrex, Ltd, of Ottawa, a company responsible for flying and interpreting millions of line kilometers of aeromagnetic data, and John S. Summer, highly respected professor of geophysics at the University of Arizona, was as follows: "In oil work ... topographic maps are studied ... to give an average terrain clearance of 1,000 ft [305 m]." The minimum clearance recommended was 700 ft (210 m). Reford later told the author (personal communication, 1991) that, after the more sensitive cesium vapor magnetometer came into widespread use in the 1970's, Geoterrex then recommended flying still higher at 1500 ft (460 m) over petroleum basins because noise became apparent in the more sensitive data flown at the 1000 ft. clearance.

If we compare the amplitude of a magnetic anomaly over a long body of limited cross-section (such as a river channel approximable by a horizontal cylinder) flown at an HRAM height of 80 m (260 ft) to the anomaly obtained at 305 m (1000 ft), the ratio is $(260/1000)^2=0.069$, or 7% (see Gay, 1965). If the flying height is increased to 1500 ft (460 m), the ratio is only 3%! During this same height increase, basement anomalies (basement at 10,000 ft) decrease only to 87% and 80%, respectively, of their initial values. Thus, there is a tremendous advantage in flying higher, if the purpose of the magnetic survey is to map basement, or even magnetic bodies buried within the sedimentary section. (See also discussion of Example E4 on this point.)

If the purpose of the magnetic survey is to map magnetic sandstones or other stratigraphic features within the sedimentary section a kilometer or so deep, beware! As Thurston, Rowe and Mitchell (1997) state: "The problem of separating magnetic responses from the [underlying rocks] is complicated by the presence of a surficial magnetic layer ... glacial deposits [that] have wavelengths on the order of 200 m... these may be aliased into the frequency band dominated by low-amplitude responses in the ... underlying [sedimentary section]."

The main point of the present paper is that even if obvious glacial till anomalies are absent, such as those over drainages (the majority of examples in this paper), the response from blanket moraines are ever-present and can be aliased into the wrong frequency band anywhere (Fig. 13, GL6 and GL7). The type of blanket response I refer to is well shown in the maps of Figures 28 and 29 and the profile of Figure 30, which bear careful scrutiny by those interested.

If the purpose of the magnetic survey is map glacial till, HRAM specifications are particularly well-suited to this purpose. Glenn, et al (1997) defined HRAM specifications as follows: "Flight line spacing of 800 m or less and terrain clearance of 150 m or less." However, many HRAM surveys are presently flown with these numbers reduced to half, and some surveys have been sold for petroleum exploration with a 200 m line spacing (a spacing more appropriate for diamond exploration). Glenn, et al, (1997) also state that HRAM specifications call for a sampling interval of 15 m or less along the flight lines and a 0.1 nT resolution or better, but all commercial surveys I am aware of at the present time adhere to these same numbers whether called "HRAM" or not.

The foregoing data and remarks lead to the inevitable conclusion that if a magnetic interpreter working with HRAM data in an area covered by glacial till has not taken steps in either the processing or interpretation phases to specifically exclude or remove the short wavelength glacial till effects (if that be at all possible), then it is fairly certain that these effects have been aliased into the anomalies from deeper sources, and the interpretation is suspect.

One dissenting voice to this argument has stated that "one man's noise is another man's signal." However, as regards glacial till anomalies, it seems to be that "one man's noise is another man's noise," as I know of no HRAM literature that has promoted the actual mapping of glacial till (although mapping boulder-filled channels would be useful in ground water exploration, in some areas).

Clearly the remarks in this paper do not apply to aeromagnetic practice in areas not covered by glacial till.

ACKNOWLEDGEMENTS

The following geophysicists, geologists, and others kindly provided information and/or examples of glacial till anomalies used in this paper, all of which is greatly appreciated:

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4. Tony Hauck
5. Wm. Hinze
6. Scott Hogg
7. Peter Hood
8. Rodney Ikola
9. Keith Jones
10. Richard Knight
11. Chris Ludwig
12. Mike Reford
13. Tony Rich
14. Ed deRidder
15. Jeff Rowe
16. Robert Schnepfe
17. Dave Skelton

Ben Opfermann of Applied Geophysics, Inc. competently performed all computer processing of AGI's magnetic data herein and prepared all illustrations.

This paper is dedicated to the memory of Robert Schnepfe (1933-1991) and Edward deRidder (1939-2002), both outstanding geophysicists in their specialties.

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APPENDIX

The author was actively engaged in gathering examples for this study when the paper was finalized. Thus, a number of examples have become available since, and these examples I include here in the appendix. In fact, additional examples have been solicited, and any that come in subsequently will also be included in this appendix.

Some might question adding new examples when the present ones more than suffice to prove that magnetic anomalies over glacial till exist and that they are a serious problem in magnetic interpretation in till-covered areas. Yet, in looking over the various examples I have obtained, it is seen that glacial till occurs in a great many different forms and in many different environments and localities and that we can learn something new from each example. This fact justifies the addition of further examples, even if reading this entire paper becomes burdensome.

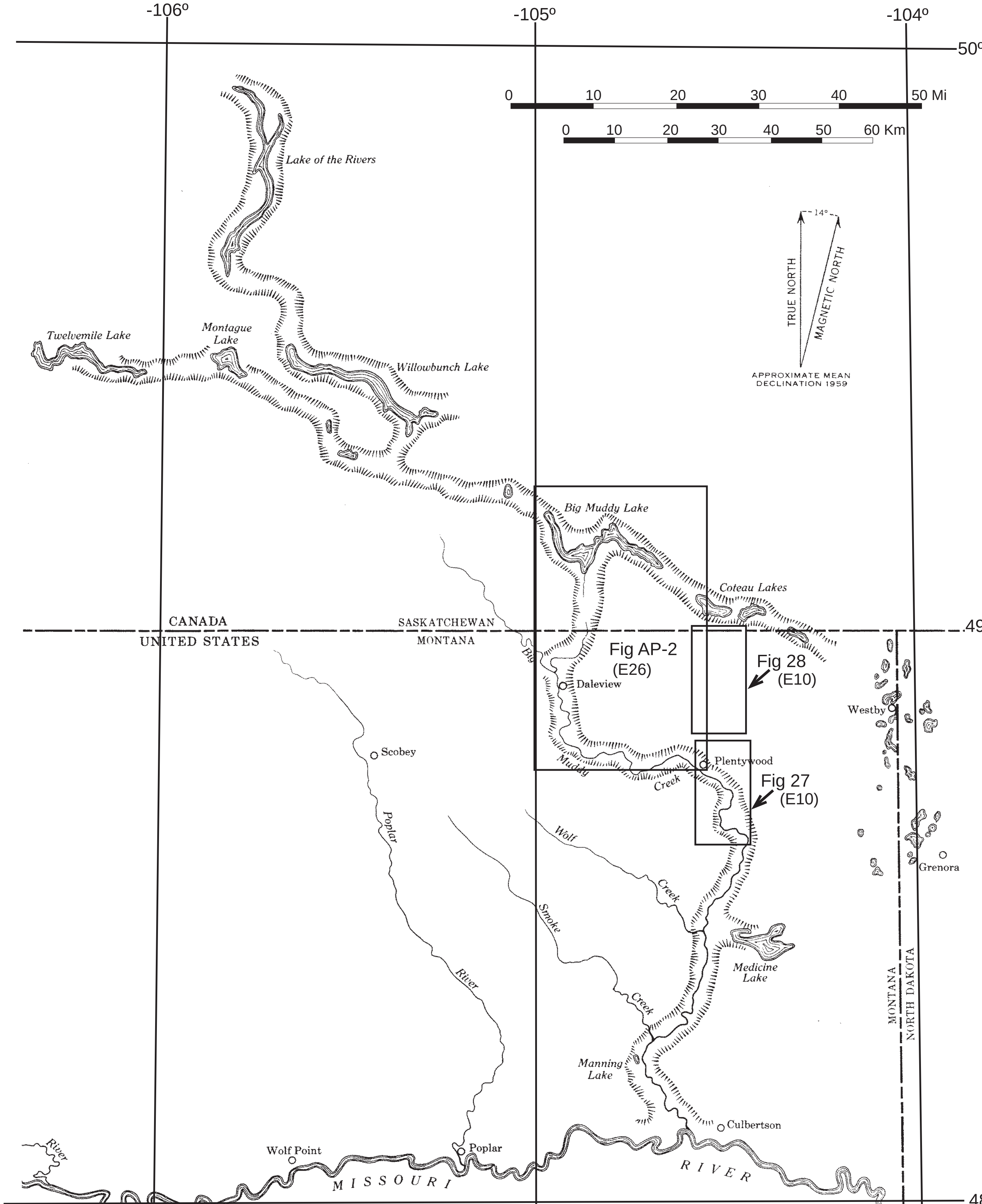

Fig. AP-1 The valley of Pleistocene Big Muddy Creek and its tributaries in Montana and Saskatchewan as mapped by USGS geologist A.D. Howard (1960). This pronounced topographic valley was a prominent tributary to the Missouri River during the last ice age and has been infilled with magnetic glacial boulders, as shown in the next figure (AP-2) and in Figure 27. Approximately 100 km (62 miles) of its length are mapped in these two figures.

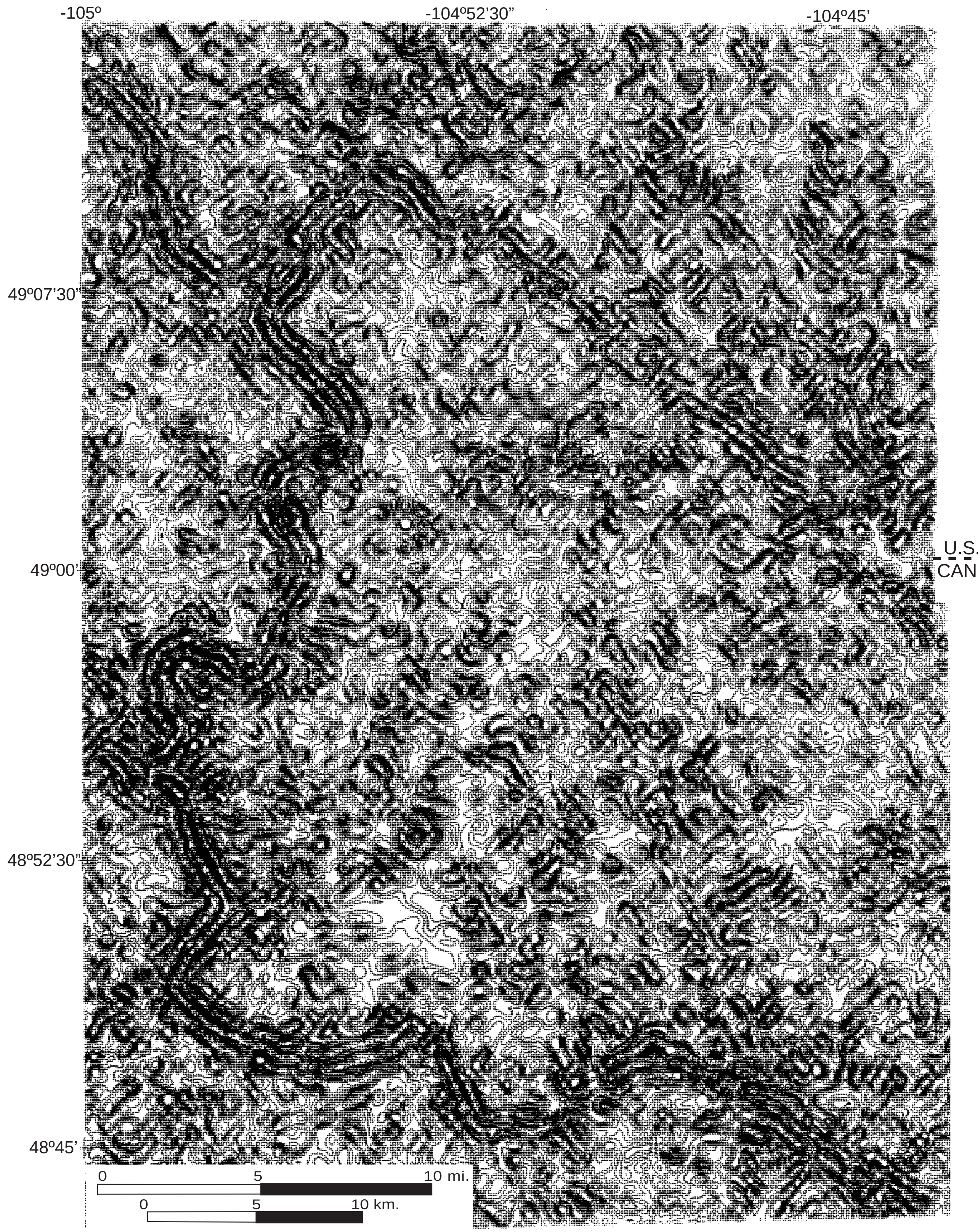

Fig. AP-2 High-frequency 2nd-Derivative map of detailed magnetics in the Plentywood area of S. Saskatchewan - NE Montana (see AP-1 for location). Big Muddy Creek and a SE tributary through present-day Coteau Lakes are clearly mapped by the magnetics over a strike length of 75 km (45 miles). High resolution aeromagnetic data courtesy of Jim Genereux of Spectra Explor. Resource Corp. and John Peirce, Geophysical Devel. & Explor. Corp., both Calgary. Processing by Applied Geophysics, Inc. This is example E26 in Figure 14.

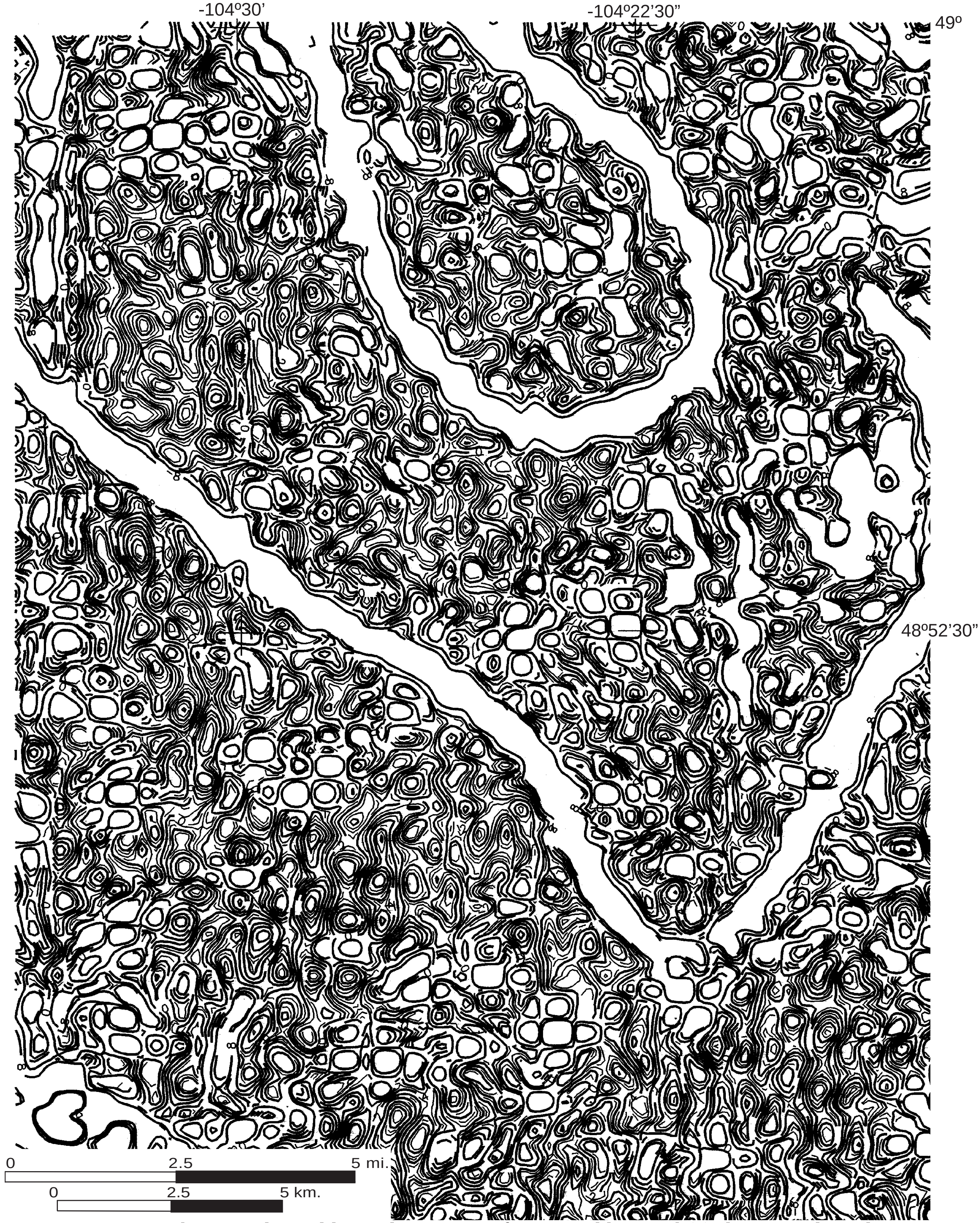

Fig. AP-3 An "ox-bow" and an old angular course of Big Muddy Creek(?) due to earlier glaciations (no present topographic expression) are emphasized in this high-frequency magnetic presentation. A short wavelength 2nd-Derivative operator was used, equivalent to that employed for Figures 27 and 28 (which this figure overlaps), but all contour lines above the median value were omitted. Processing by Applied Geophysics, Inc.; data courtesy of Pearson, deRidder and Johnson, Denver, Richard Hansen, manager. This is example E27 in Figure 14.

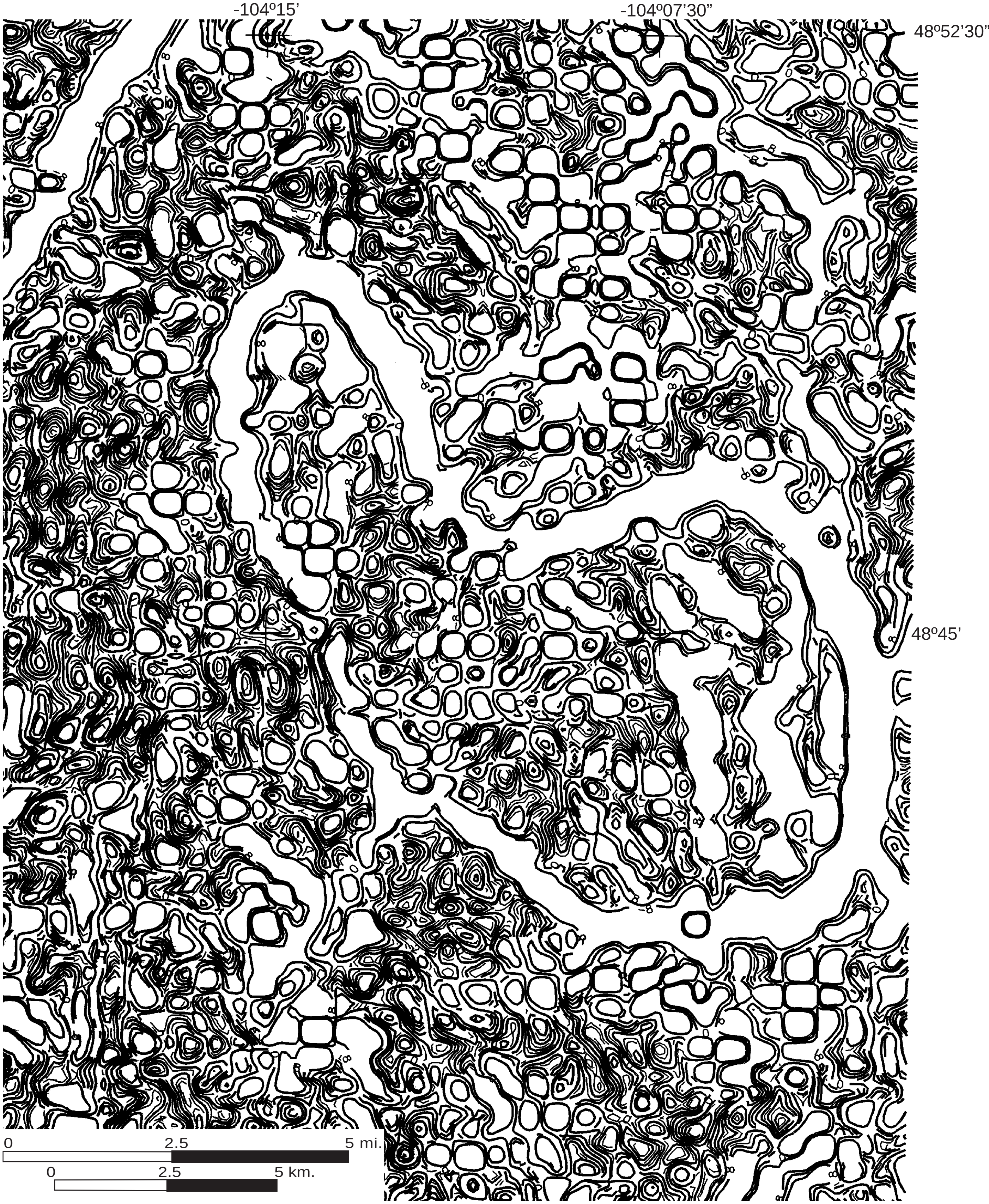

Fig. AP-4 This is a SE extension of the previous figure (AP-3) showing two buried ox-bows, which apparently formed separately at different times in previous glaciations. Same remarks regarding data on previous figure apply. This is example E28 in Figure 14.

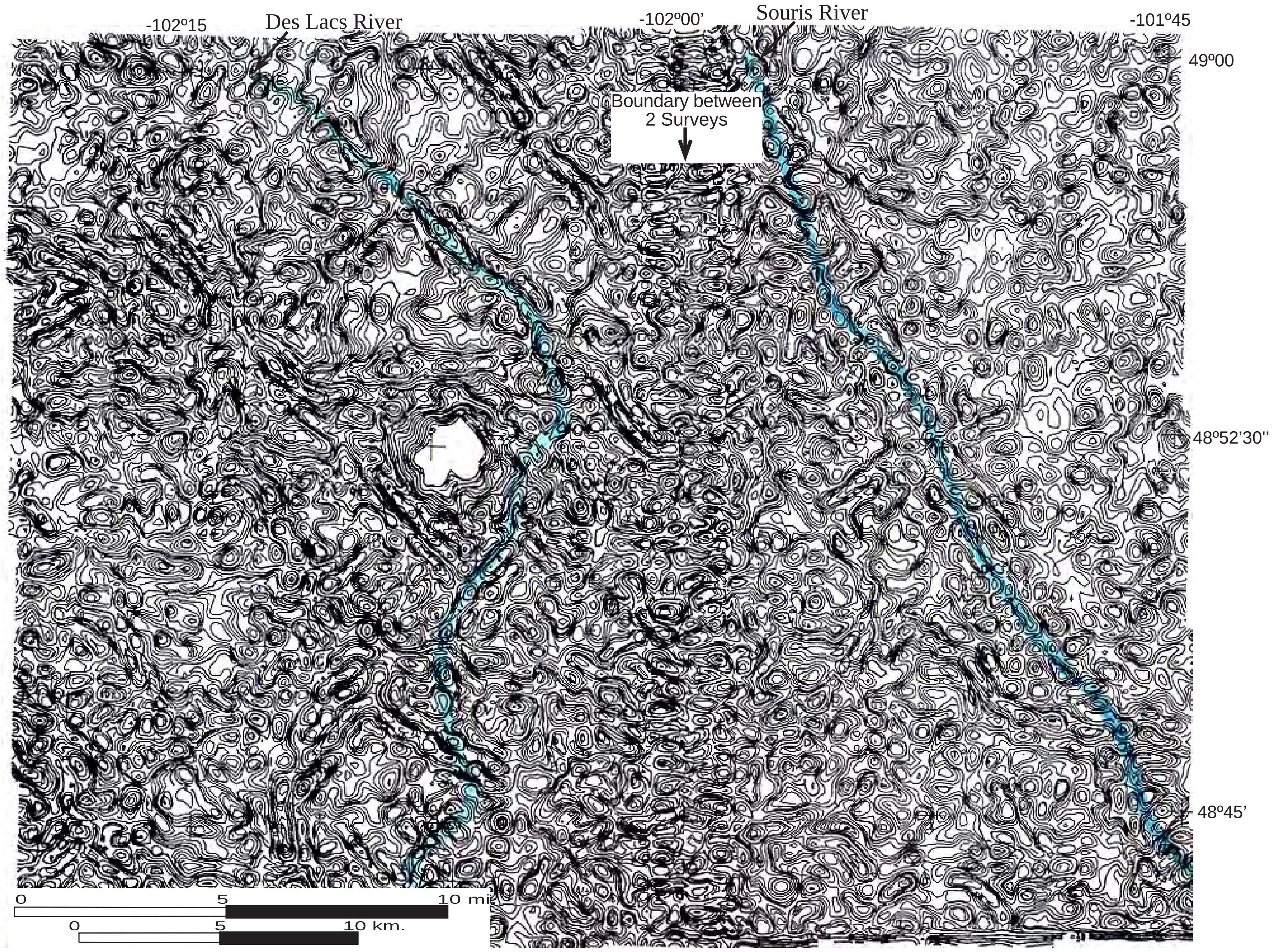

Fig. AP-5 Two present-day north-south trending rivers cross this area in North Dakota adjacent to the Canadian border. The Souris River on the east (see next figure, AP-6) is not visible on the magnetic data, although occasional short stretches of magnetics do coincide. The Des Lacs River on the west is more notable, especially the northern half. What is remarkable, however, is the complex pattern of linear magnetic anomalies corresponding to earlier glaciations. Probably two or more pre-Wisconsin glaciations are represented here. Magnetic data from same survey as Fig. AP-2. Processing by Applied Geophysics, Inc. This is example E29 in Figure 14.

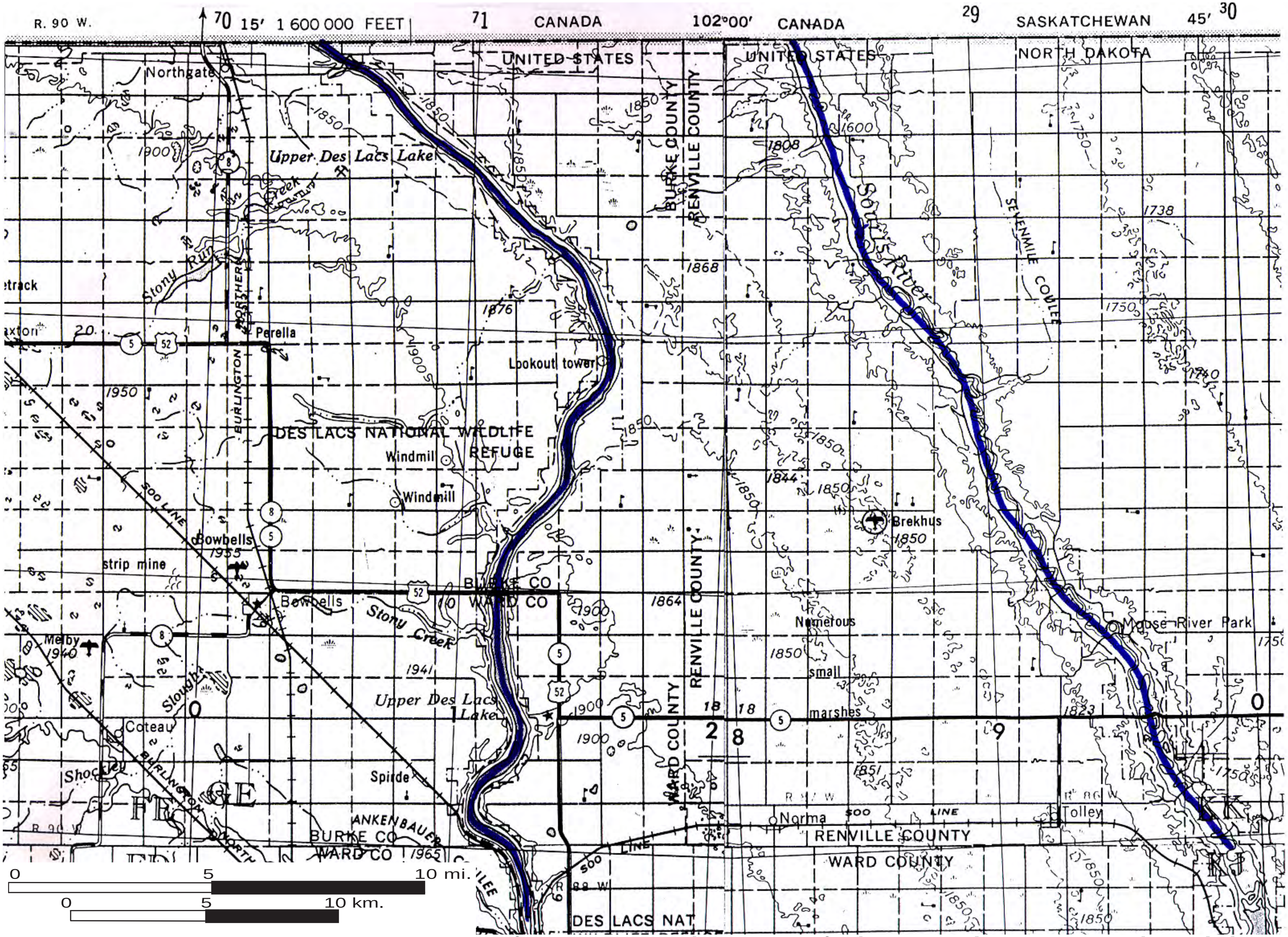

Fig. AP-6 Topographic map corresponding to previous figure (AMS 1°x2° sheet). Except for the Souris and Des Lacs rivers, there is little or no correlation of the pattern of linear magnetic anomalies (corresponding to old drainages) with the topography, which is extremely flat in this area. The average surface gradient on the west side of the map is only 2 to 3 feet per mile (0.5/1000).