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Technical Note TN-12

APPLICATION OF SIMPLE LOOP MODELS TO THE INTERPRETATION OF TRANSIENT ELECTROMAGNETIC SURVEYS IN A RESISTIVE ENVIRONMENT

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February, 1984.

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1. INTRODUCTION

In the spring of 1983 demonstration surveys using the EM37 transient EM system were carried out in Sweden, Finland, and Norway at the sites shown in Figure 1. In all cases the terrain was known beforehand to be resistive. Before each survey the target, as described by the client, was simulated with a simple loop model and the response calculated as a function of transmitter loop size and position. This information was used to locate the actual transmitter loop.

For each of the three surveys it was possible to accurately match the measured survey profiles of dB/dt (at late time) with the response from a loop model which in turn agreed well with the known geology. The survey decay curves were also integrated numerically to produce profiles of the magnetic field B (rather than its time derivative) to illustrate the feasibility of this technique.

This short note briefly describes the simple loop program, discusses the merits of numerical integration of the transient response to generate B, and illustrates both features with data from the three surveys.

2. SIMPLE PLATE/LOOP PROGRAM

In many parts of the world base metal deposits are typically limited in thickness to a few meters and yet have depth and strike extent of several tens or hundreds of meters. A thin plate-like model is a useful representation of such targets.

Annan (1974) describes a technique which permits accurate calculation of the vortex current flow in a thin conductive rectangular plate located in free space and excited by an arbitrary primary magnetic field. His procedure for calculating the currents, and thus also the secondary magnetic field, has been incorporated into a computer program developed at the University of Toronto and described by Dyck, Bloor and Vallée (1980).

The program, which includes the response from relatively high order eigencurrents, is quite accurate. However it is complex and cannot be run in a reasonable length of time on currently available field portable computers.

Furthermore, survey experience with the EM37 (which has the facility for making accurate measurements of the transient decay at early time) shows that the transient response from conductive targets usually has a much larger amplitude at early time than can be accounted for by the presence of high order eigencurrents. The reasons for this are not clearly understood, however the presence of a conductive halo can greatly enhance the early response, as shown by Nabighian (1971). McNeill et al (1984) have suggested that the response from galvanic currents can also make a large contribution at early time, even in resistive ground. Obviously neither of these effects are included in the University of Toronto plate program.

Fortunately important information about bounded conductors can be obtained from measurements made at late time, when the response from high order eigencurrents (with short time-constants) has died out and the response from the lowest order eigencurrent, decaying exponentially with a single time-constant, dominates (Kaufman, 1978).

Simple exponential decay over the later portion of the transient response is often seen in surveys carried out in relatively resistive environments.

There were thus good reasons for determining which plate parameters controlled the late time response. A parametric study was performed using calculated results from the University of Toronto program supplemented by actual physical measurements of the response from a series of model plates.

The results of the study (McNeill, 1982) demonstrated that the late stage response is a simple function of the plate parameters. Indeed if a and b are the minor and major dimensions of the full plate, it can be replaced by a single rectangular loop of wire of dimensions 0.7a and 0.7b centered on the plate, as long as the response is not measured in close proximity to the plate. The wire loop carries a current described by $I_o \exp(-t/\tau)$, where I_o is essentially a function of the product of the primary magnetic field H_o averaged over the plate and a. The late-stage time constant τ is determined by the product of S, the plate conductance (also called the conductivity-thickness) and a.

The surprisingly simple dependence of the plate response on S and a facilitates survey interpretation. The fact that the response can be relatively accurately approximated by that from an appropriate wire loop permits use of a simple fast computer algorithm to calculate the late stage plate response. In the Geonics approximate plate program I_o and τ are given by

$$I_o = 0.64\ a\ H_o\ f_1\ (b/a)$$

$$\tau = [\mu_o\ Sa\ f_2\ (b/a)]/10$$

where μ_o is the permeability of free-space, f_1 (b/a) and f_2 (b/a) are empirically derived, slowly varying functions of (b/a) as shown in Figure 2, and the other parameters have already been defined.

The limitations of this simple model must be clearly understood. The program is based on free-space modeling and can only be expected to give useful results in relatively resistive ground. Since the continuous current distribution in the plate has been replaced with a single current filament in a loop, the program will give inaccurate results close to the plate. Improving the accuracy of the model by better approximation of the current distribution is straightforward but increases the running time on field portable computers. The program should not be used when the transmitter is in close proximity to very large targets, since higher order eigencurrents can then be expected to contribute significantly to the response even at late time. Finally, since it is a late stage program it must only be used at late time - i.e. when the measured target decay has become exponential with a single well defined time constant.

These restrictions have not proved to be too constraining and surveys carried out over the past several years have shown the program to be useful for interpretation. The standard procedure is as follows:

(1) Select from the measured survey profiles of dB/dt a location where the target is clearly distinguishable.
(2) Using the homogeneous half-space or horizontal thin sheet model (depending on which gives the best fit) subtract the half-space or conductive overburden response from the profile for each time channel of interest.
(3) Plot the logarithm of the residual at the target maximum as a function of time to determine whether the response becomes exponential (a straight line on log-linear graph paper). If this is not the case the simple plate program must not be used.
(4) If the response is exponential calculate the late-stage time constant. Check that exponential decay commences at time approximately equal to the late-stage time constant (survey

experience has shown that this should be the case).

(5) Examine the survey profiles at time greater than the calculated late-stage time constant to ensure that their shape is no longer varying with time - i.e. that the target currents are now stationary and simply decaying with time.

(6) Using trial and error, match the profiles generated by the plate program to the survey profiles. This can generally be achieved to satisfactory accuracy in about six tries as long as a plate model is appropriate.

3. TARGET IMPULSE AND STEP RESPONSES

The EM37-3 and most other transient electromagnetic systems generate a target response by causing an essentially static magnetic field at the target to be abruptly terminated. They are said to measure the target impulse response since the induced emf which drives the vortex eddy currents is, in resistive ground, proportional to the time derivative of the primary magnetic field (and the transmitter current) and is thus an impulse function.

On the other hand the UTEM system employs a triangular transmitter current waveform, the time derivative of which is a step function, and this system is said to measure the step response of a target.

There are some significant differences between the impulse and step response. For example if the target is confined it is easy to show that at the late stage the impulse response is proportional to $(1/\tau)\exp(-t/\tau)$ whereas the step response is proportional to $\exp(-t/\tau)$. Therefore the impulse response from targets with short time-constant will be relatively enhanced compared with the step response. This is an advantage if we are searching for poor conductors, but a disadvantage if we are searching for good conductors located in close proximity to poor ones. It is apparent that it will sometimes be useful to obtain both the impulse and the step response.

Fortunately linear systems theory shows that the target step response can be obtained by integrating the impulse response. Our receiver coil measures dB(t)/dt. Taking the integral of the transient response

$$\int_{\infty}^{t} \frac{dB(t)}{dt}\, dt = B(t) \quad \text{if} \quad \lim_{t\to\infty} B(t)\to o$$

shows that the target step response would be obtained if we measured the magnetic field itself rather than the time derivative. Conversely if a well resolved transient decay curve of dB/dt is available, simple numerical integration can be used to obtain the transient curve of B(t) and thus the step response. Furthermore since integration is a smoothing process the already excellent signal-to-noise ratio usually obtained with the EM37 will be further enhanced. In order to obtain an accurate integral, particularly at early time, many narrow gates must be employed to get an accurate measurement of dB/dt.

Until the advent of acceptable wide-band magnetometers, a satisfactory approach to determining the approximate step response lies in post-measurement numerical integration of dB/dt. Although such a procedure requires a large dynamic range in the instrumentation, it offers the compensating advantage of automatically increasing the signal-to-noise ratio for poor conductors which, because of their short time constants, require the use of narrow (and thus noisy) gates for proper resolution. Note, however, that at late time the values of B are subject to a zero-error, since in order to integrate to $t=\infty$ we must extrapolate the transient, based on the last measured values; dB/dt should always be used for the determination of τ.

4. TRANSMITTER TURN-OFF TIME CORRECTION

The procedure of integrating the decay curve of dB/dt to obtain the step response assumes that the measured response is indeed the impulse response, which in turn implies that the transmitter current turn-off takes place infinitely quickly. In fact, however, it is impossible to instantaneously switch off high current in a large loop whilst maintaining a finite voltage across the loop terminals. Our solution has been to design the transmitter so that the current turn-off exhibits a rapid linear-ramp decay with time. This results in a target emf which is accurately rectangular rather than an impulse function.

Although the duration of the rectangular pulse is short (typically 450μsec for a 300 x 600 meter transmitter loop carrying a peak current of 30 amperes) the finite length can cause distortion of the target response. This distortion is appreciable for short time constant targets at all measurement time, and for homogeneous and layered earth response at early time. For both situations, removal of the distortion is necessary in order to compare survey results with theoretical modeling based on an infinitely fast transmitter turn-off. To solve the problem Geonics has developed a computer algorithm which employs as input both the measured values of dB/dt at each survey point along the profile and the known transmitter turn-off time. The program calculates profiles of B and dB/dt, both corrected for finite turn-off time. As will be seen in the following case histories it is routinely used for survey interpretation.

5. SURVEY RESULTS AND INTERPRETATION

All of the surveys were carried out with a standard EM37, for which the location of the various time gates is shown in Table 1. The gates are sufficiently narrow that no correction for finite gate width is necessary.

Table 1. EM37 Gate Center Locations

Channel	Location(msec)	Channel	Location(msec)
1	0.089	11	0.876
2	0.110	12	1.087
3	0.140	13	1.40
4	0.177	14	1.77
5	0.220	15	2.21
6	0.280	16	2.82
7	0.355	17	3.57

Channel	Location(msec)	Channel	Location(msec)
8	0.443	18	4.46
9	0.563	19	5.66
10	0.712	20	7.16

For each survey the profile is matched with the response from a rectangular wire loop as outlined in Section 2. It is, of course, the equivalent plate which is compared with the known geology.

SURVEY #1: Malå (Sweden)

Figure 3 shows a plan view of the target which is a relatively small, dipping, plunging, tabular massive sulphide deposit located in a resistive diorite/gabbro host. It is defined by drilling as indicated on the figure (target thickness averaged a few meters).

An earlier Sirotem survey, which had responded to the target, suggested the possibility of a further conductor to the south, so that a single, long survey line was set out as shown. Two components, X (along line) and Z (vertical), were measured. The raw data is shown in Figure 4 and the transient decay in Figure 5.

Since for this survey the profiles of dB/dt corrected for finite transmitter turn-off and of B add little, they are not shown.

It is evident from Figure 4 that the half-space contribution is small and that there is no indication of a conductor further south. Figure 5 shows that the late-stage transient decay is exponential after about 2.5 msec, with a time constant of 2.35 msec. Furthermore, examination of channels 15-20 in Figure 5 confirms that beyond this time the responses are stationary (i.e. the shape of the profiles is no longer a function of time).

Figure 6 illustrates the best plate fit to the data of channel 15; the location of the plate model is shown in Figure 3. Although slightly offset to the south from the indicated body, the general location of the plate is in reasonable agreement and the geometry and depth in excellent agreement. It must be remembered that in this case the approximate dimensions of the body were known beforehand and used as inputs to the model. For example the measured data from a single survey line with only two field components could not be expected to yield an accurate strike length.

SURVEY #2: Hannukainen (Kolari, Finland)

Figure 7 shows a plan view of the survey area. The Kivivuopio orebody is a gently dipping, strata-bound, skarn iron-ore deposit located at a depth of 300 - 700m. It had been detected and outlined by magnetics and extensive AMT surveying as well as other geophysical methods (Pietilä and Hattula, 1982), and confirmed by drilling as indicated. Again the bedrock is resistive; thickness of the deposits in this region ranges from a few meters to 40 m. An objective of the survey was to determine whether the body continued down-dip to the west.

Raw survey profiles are shown in Figure 8, profiles corrected for finite transmitter turn-off time in Figure 9, profiles of B in Figure 10, and the transient decay curve again in Figure 5. The latter indicates exponential decay commencing at about 3 msec, with a time constant of 3.66 msec. Late stage behaviour beyond this time is confirmed by the profiles of Figure 8 (the continuing change of the profile at the east end of the line is thought to be due to the adjacent conductor).

The two "glitches" at the transmitter wire appear to have been caused by operator error. However they offer an interesting example of the effect of correcting for finite transmitter turn-off. Since they are of low time constant (less than the transmitter turn-off time of 210 μsec), correcting for the turn-off time substantially enhances their response (Figure 9), whereas integrating to produce profiles of B reduces their response as well as reducing the overall dynamic range required to plot the data (Figure 10).

Figure 11 illustrates the best-fit plate model; the location of the plate is shown in Figures 7 and 12. It will be seen that the fit between the plate and target (at an average depth of 500 m) is good; additional experimentation with the plate model confirmed the lack of down-dip extension to the target.

Again both dimensions of the target were approximately known beforehand and a single line survey could not determine the strike extent nor, with only two components, that the target also has a shallow plunge.

SURVEY #3: Kautokeino (Norway)

Figure 13 shows a plan view of the location of the two survey lines. Little is known by the authors about the geology of the region except that sulphides are located at discontinuities in graphite, which is thus the target. An early Turam survey had located one conductor which was drilled: some years later the survey was reinterpreted and a second conductor located, on which a drill had been set up just before the EM37 survey was performed.

The raw survey data from line 1400 is shown in Figure 14, the computed profiles of B in Figure 15, and a transient decay (which shows a late-stage time constant of 3.5 msec) in Figure 5. The profiles of dB/dt with zero turn-off time add little, as do the profiles for line 1700, so they are not shown.

Two conductors, one good and one poor, are clearly evident in Figure 14. It was in fact the poorer conductor which had been initially picked and drilled on the basis of the Turam survey. The benefit of integrating the response for this case is indicated in Figure 15. Were the conductors closer together the advantage of B over dB/dt would be more apparent.

Modeling with the plate program now required matching four profiles as illustrated in Figure 16; the location of the dipping and plunging plate is shown in Figure 13. As is evident from Figure 13 the modeling suggested that the drill would just intersect the top of the target at a distance of 110m; a few weeks later drill intersections were confirmed at 108-111m and 113-116m, with no further intersections to 160m.

SUMMARY

The survey data presented in this short note demonstrates the usefulness of a simple loop model for interpreting the results of transient EM surveys using large loop Turam-type transmitters, as long as neither the source nor the receiver is close to the plate, and the ground is reasonably resistive (in excess of a few hundred ohm-meters). Furthermore the loop must not be much larger than the transmitter, although the data from Hannukainen suggest that it can still be reasonably large.

Arguments and data are presented which indicate the usefulness of numerically integrating the transient curves so as to obtain profiles of the magnetic field as well as its time derivative, and thus of the target step response as well as the impulse response.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the assistance given by Boliden Aktiebolag (Malå), Rautaruukki Oy (Hannukainen), and Prospektering A/S (Kautokeino). These companies helped in carrying out the surveys, supplied geological and geophysical data about the sites and gave permission to publish the results.

The work described herein was partially funded by National Research Council of Canada IRAP Grant TES 666.

REFERENCES

Annan, A.P. (1974), The equivalent source method for electromagnetic scattering analysis and to geophysical application; Ph. D thesis, Memorial University of Newfoundland, 242 p.

Dyck, A.V., Bloor, M., Vallée, M.A., 1980, User manual for programs plate and sphere; Research in Applied Geophysics no. 14, Geophysics Laboratory, University of Toronto.

Kaufman, A., 1978, Frequency and transient responses of electromagnetic fields created by currents in confined conductors: Geophysics, V.43, p.1002-1010.

McNeill, J.D. 1982, Interpretation of large-loop transmitter transient electromagnetic surveys: 52 Annual International SEG Meeting, Dallas, Texas, Oct. 19, 1982. (In the abstract the functions f_1 and f_2 should be interchanged and the "b" following 0.64 should be replaced by "a").

McNeill, J.D., Edwards, R.N., Levy, G.M., 1984, Approximate calculations of the transient EM response from buried conductors in a conductive half-space: Geophysics, (in press).

Nabighian, M.N., 1971, Quasi-static transient response of a conducting permeable two-layer sphere in a dipolar field: Geophysics, V.36, p.25-37.

Pietilä, R., Hattula, A., 1982, An application of audio-frequency magnetotellurics and charge potential method in skarn iron ore prospecting in the Rautuvaara area, northern Finland. 44th Annual EAEG Meeting, Cannes, France, June, 1982

LIST OF ILLUSTRATIONS

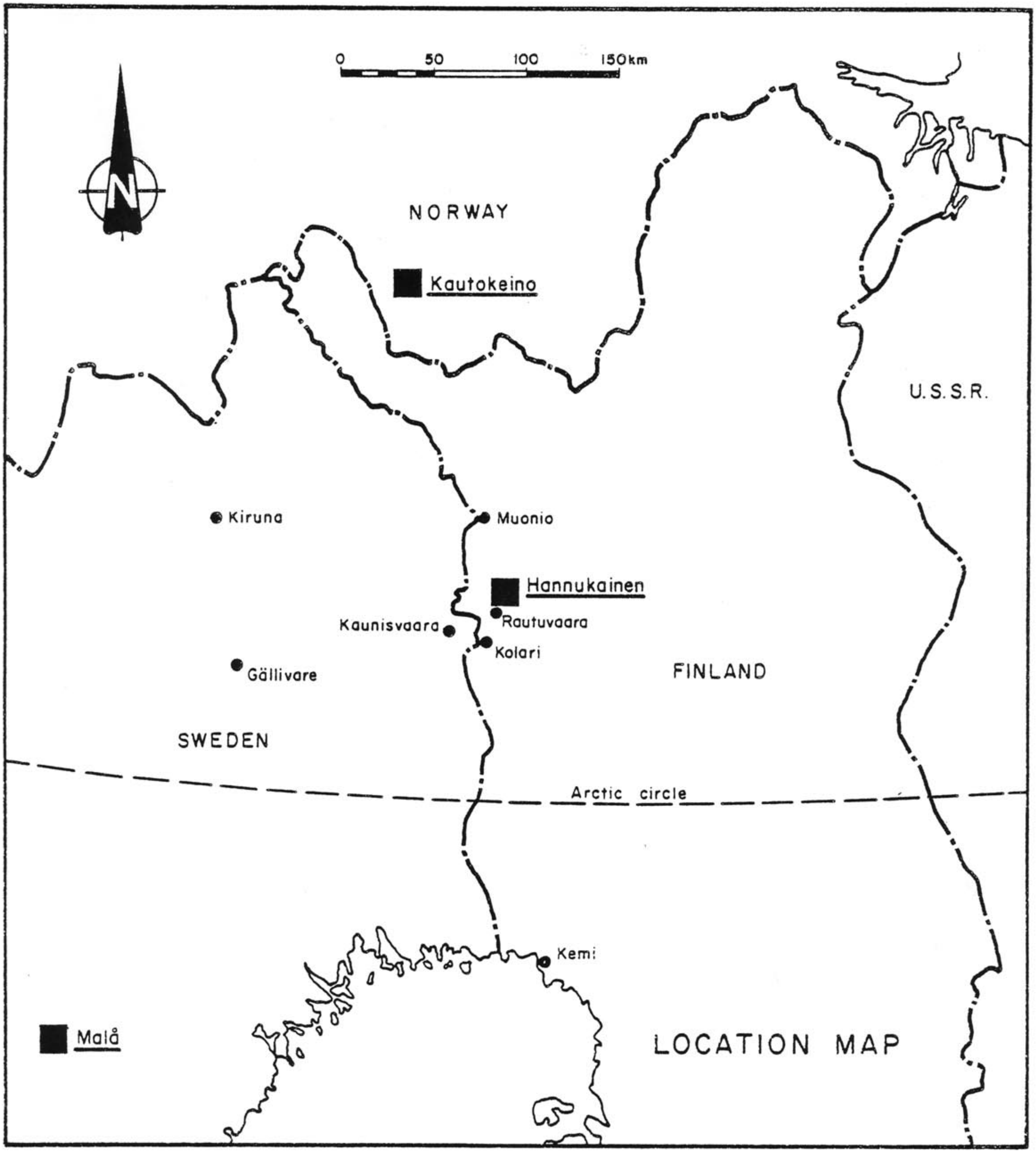
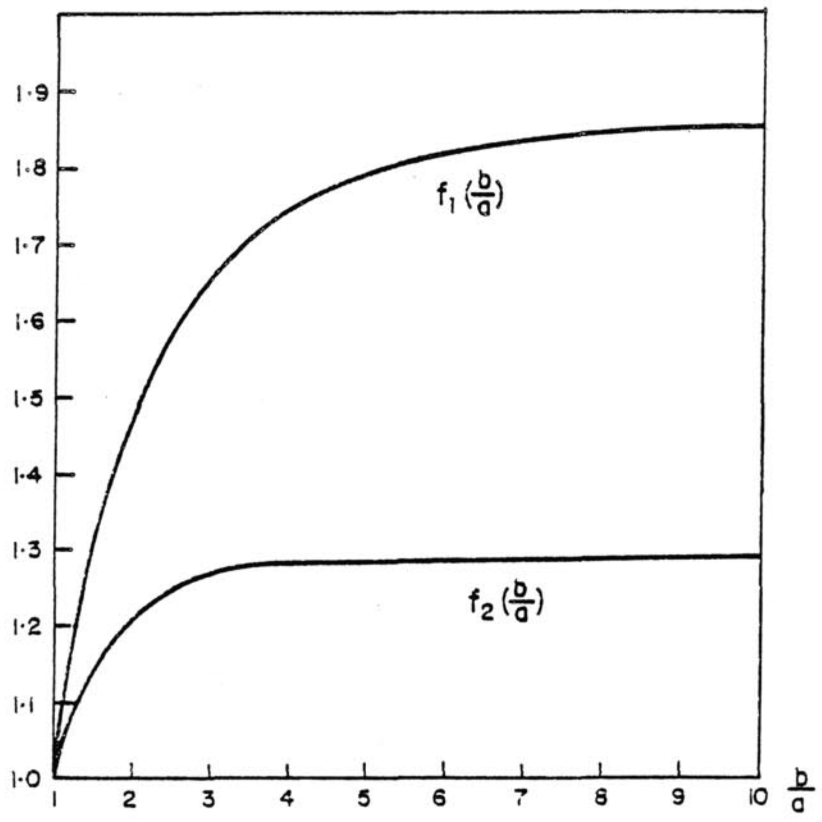

0
50
100
150km
N
NORWAY
Kautokeino
U.S.S.R.
Kiruna
Muonio
Hannukainen
Rautuvaara
Kaunisvaara
Kolari
Gällivare
FINLAND
SWEDEN
Arctic circle
Kemi
Malå
LOCATION MAP

Figure 1.



1·9
1·8
1·7
1·6
1·5
1·4
1·3
1·2
1·1
1·0
1
2
3
4
5
6
7
8
9
10
$\frac{b}{a}$
$f_1(\frac{b}{a})$
$f_2(\frac{b}{a})$

Figure 2.

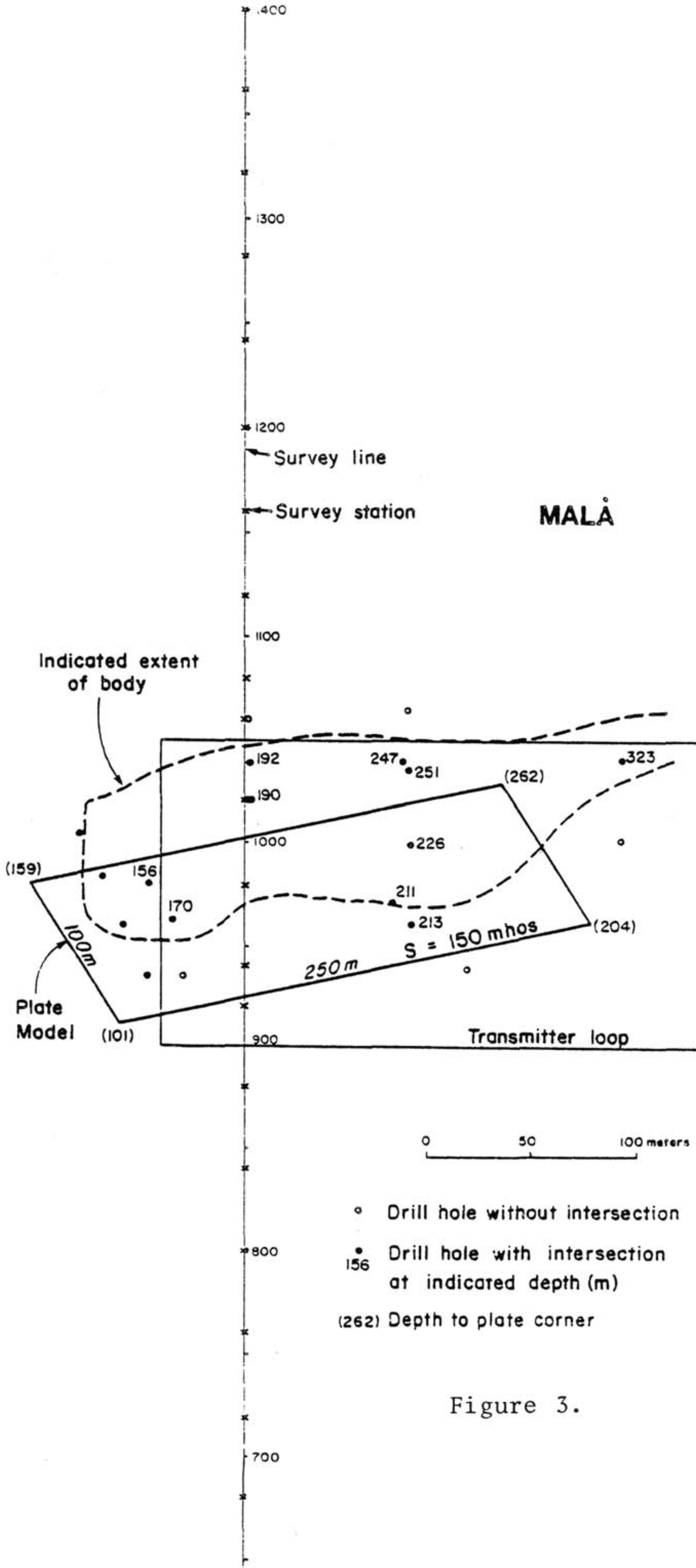
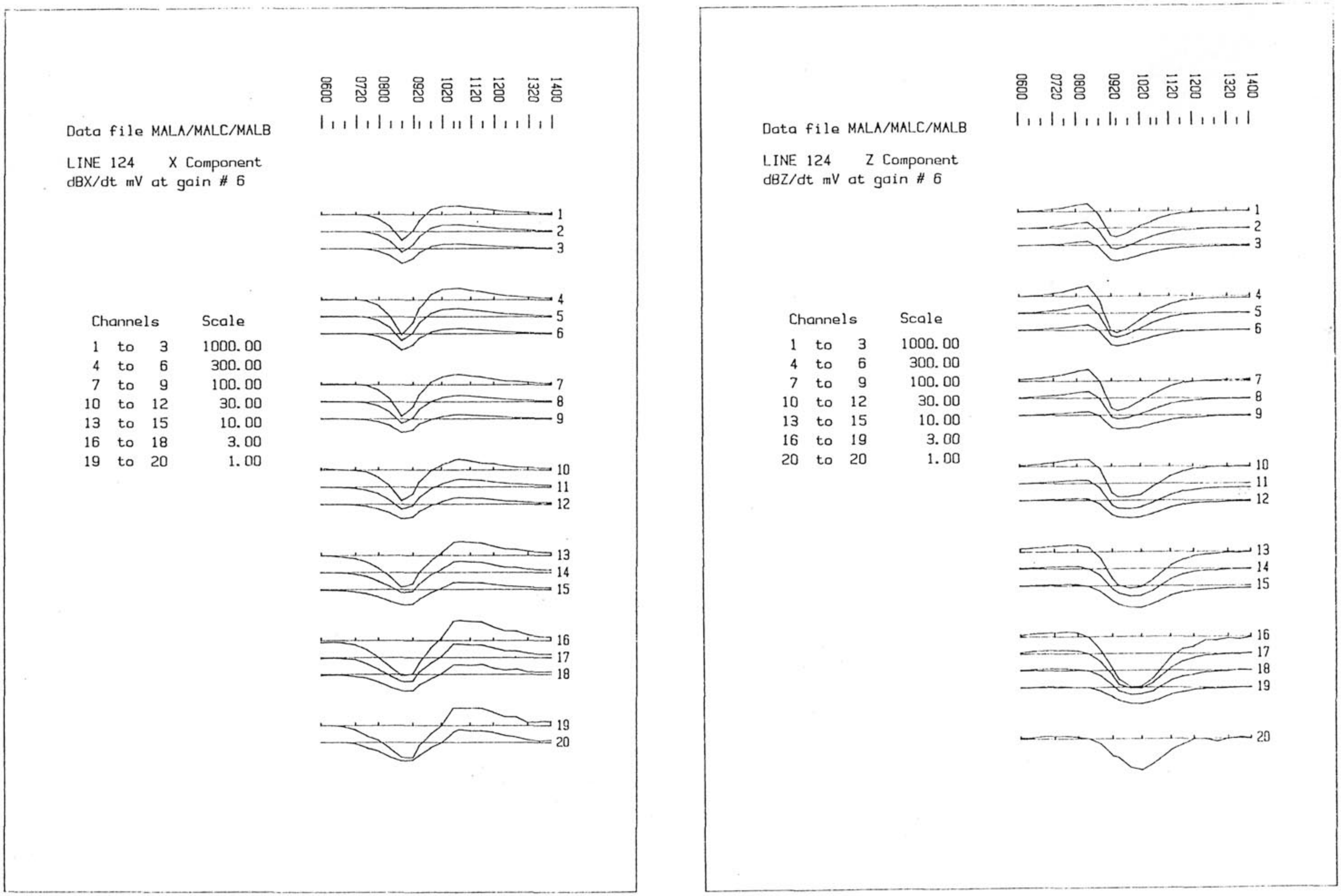

1400
1300
1200
Survey line
Survey station
MALÅ
1100
Indicated extent of body
192
247
251
323
(262)
190
1000
226
(159)
156
170
211
213
S = 150 mhos
(204)
100m
250m
Plate Model
(101)
900
Transmitter loop
0
50
100 meters
Drill hole without intersection
156 Drill hole with intersection at indicated depth (m)
(262) Depth to plate corner
800
700

Figure 3.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LINE 124 X Component
dBX/dt mV at gain # 6

Channels	Scale
1 to 3	1000.00
4 to 6	300.00
7 to 9	100.00
10 to 12	30.00
13 to 15	10.00
16 to 18	3.00
19 to 20	1.00

Data file MALA/MALC/MALB

LINE 124 Z Component
dBZ/dt mV at gain # 6

Channels	Scale
1 to 3	1000.00
4 to 6	300.00
7 to 9	100.00
10 to 12	30.00
13 to 15	10.00
16 to 19	3.00
20 to 20	1.00

Figure 4.

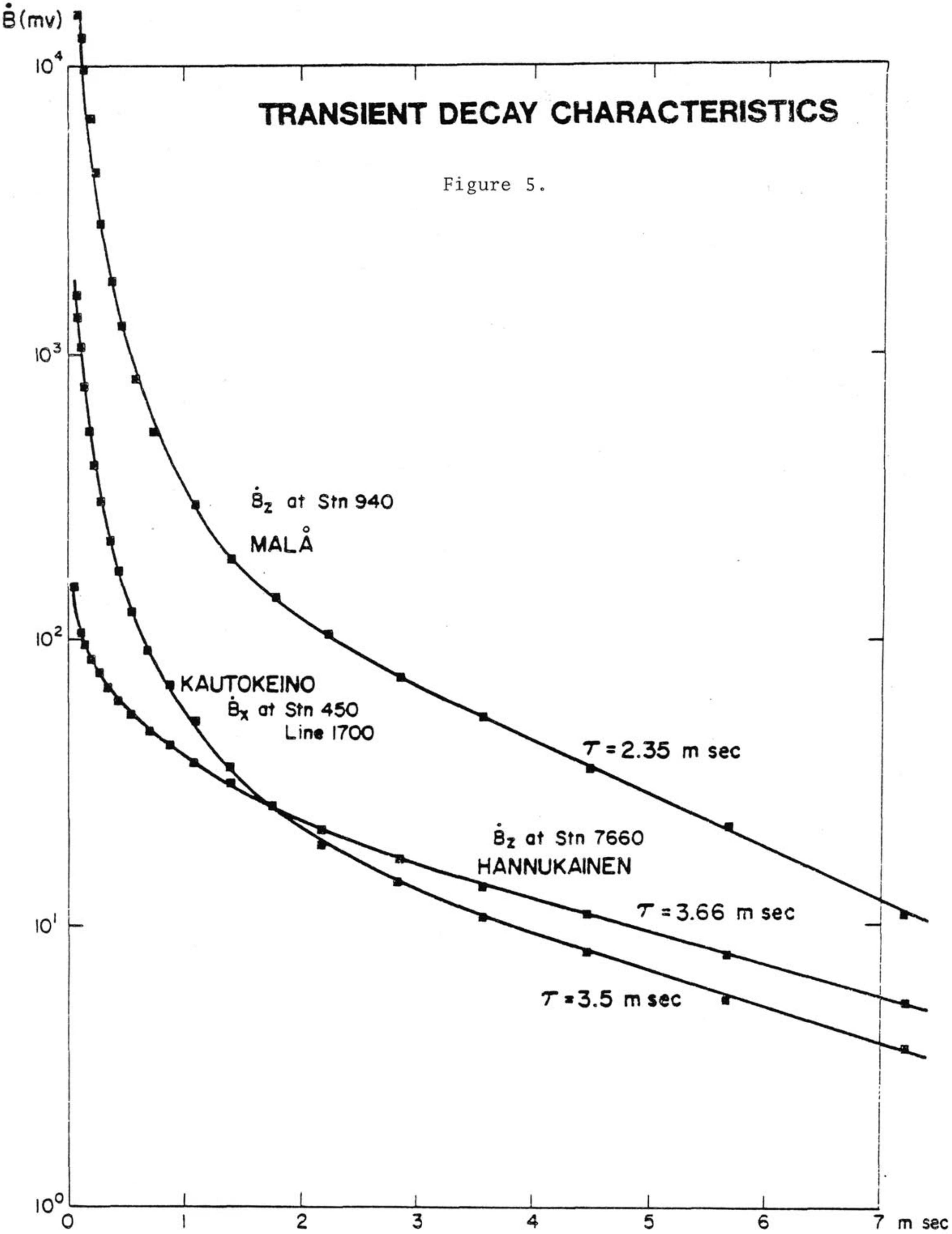


Figure 5.

TRANSIENT DECAY CHARACTERISTICS
$\dot{B}$(mv)
10^4
10^3
10^2
10^1
10^0
$\dot{B}_z$ at Stn 940
MALÅ
KAUTOKEINO
$\dot{B}_x$ at Stn 450
Line 1700
τ = 2.35 m sec
$\dot{B}_z$ at Stn 7660
HANNUKAINEN
τ = 3.66 m sec
τ = 3.5 m sec
0
1
2
3
4
5
6
7 m sec
)

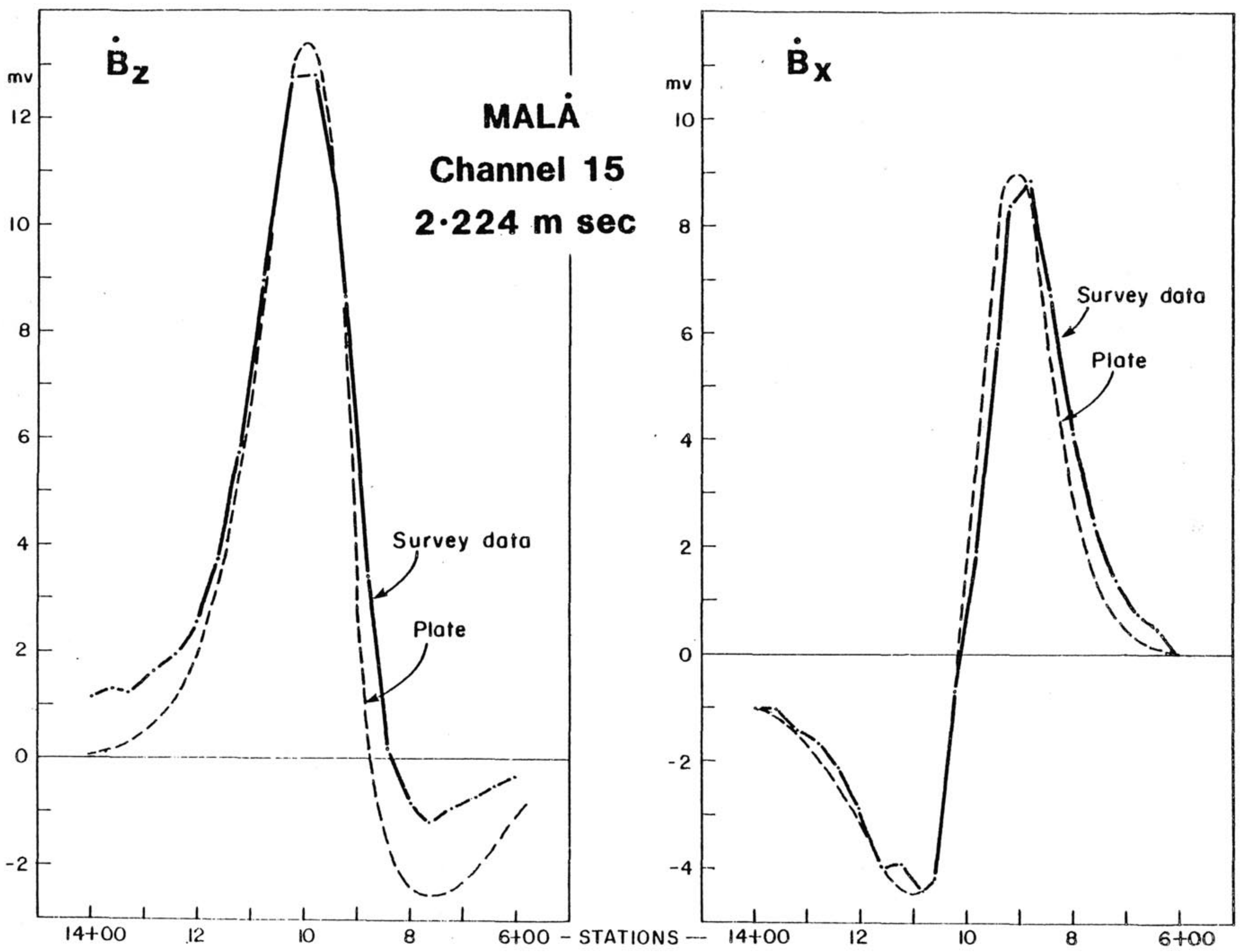

Ḃz
mv
12
10
8
6
4
2
0
-2
MALÅ
Channel 15
2·224 m sec
Survey data
Plate
14+00
12
10
8
6+00
STATIONS
Ḃx
mv
10
8
6
4
2
0
-2
-4
Survey data
Plate
14+00
12
10
8
6+00

Figure 6.

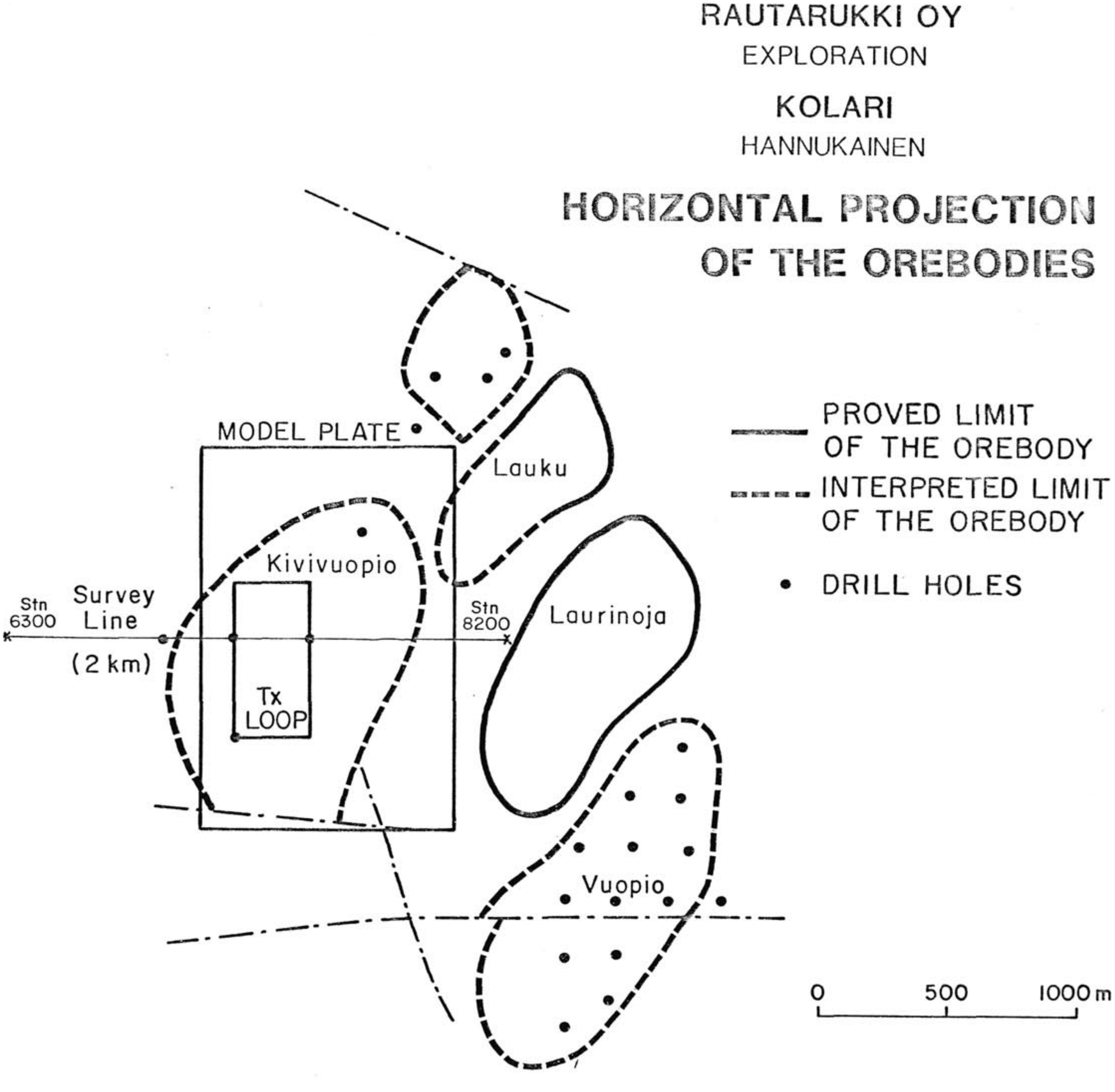

RAUTARUKKI OY
EXPLORATION
KOLARI
HANNUKAINEN
HORIZONTAL PROJECTION OF THE OREBODIES
MODEL PLATE
Lauku
Kivivuopio
Laurinoja
Vuopio
Stn 6300
Survey Line
(2 km)
Stn 8200
Tx LOOP
PROVED LIMIT OF THE OREBODY
INTERPRETED LIMIT OF THE OREBODY
DRILL HOLES
0
500
1000 m

Figure 7.

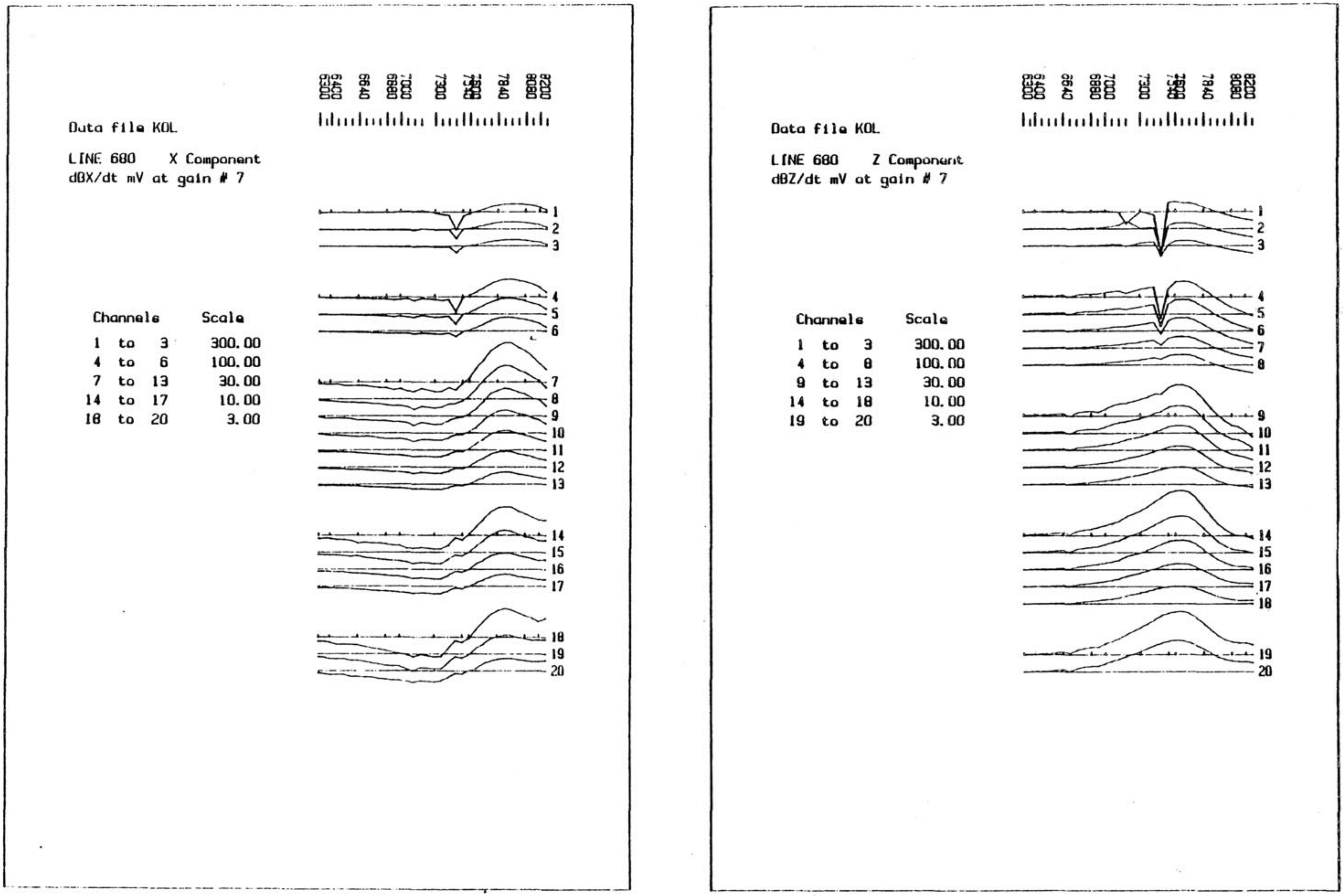
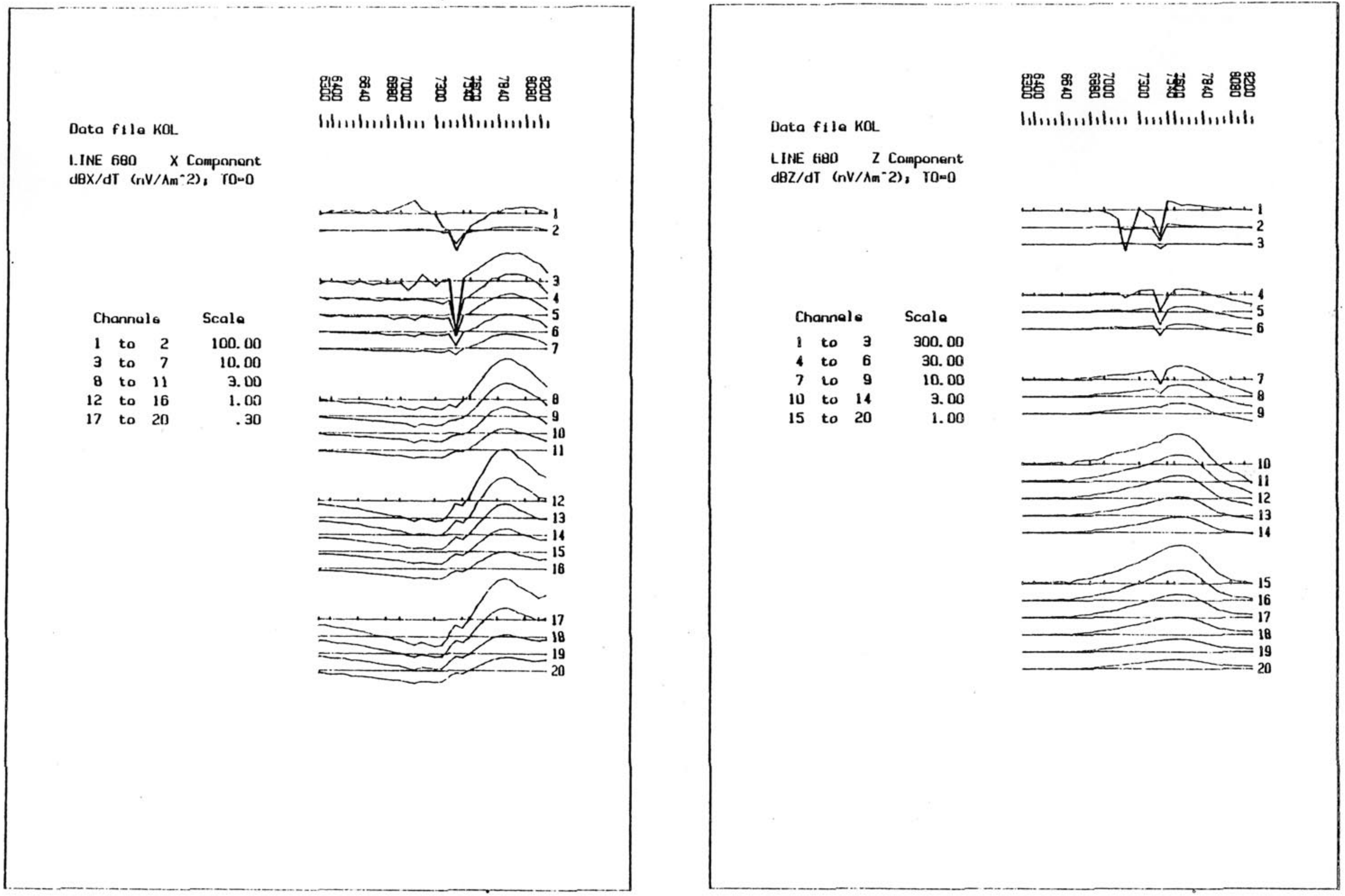

Data file KOL
LINE 680 X Component
dBX/dt mV at gain # 7
Channels Scale
1 to 3 300.00
4 to 6 100.00
7 to 13 30.00
14 to 17 10.00
18 to 20 3.00
6300
6400
6640
6880
7000
7300
7540
7600
7840
8080
8200
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
Data file KOL
LINE 680 Z Component
dBZ/dt mV at gain # 7
Channels Scale
1 to 3 300.00
4 to 8 100.00
9 to 13 30.00
14 to 18 10.00
19 to 20 3.00

Figure 8.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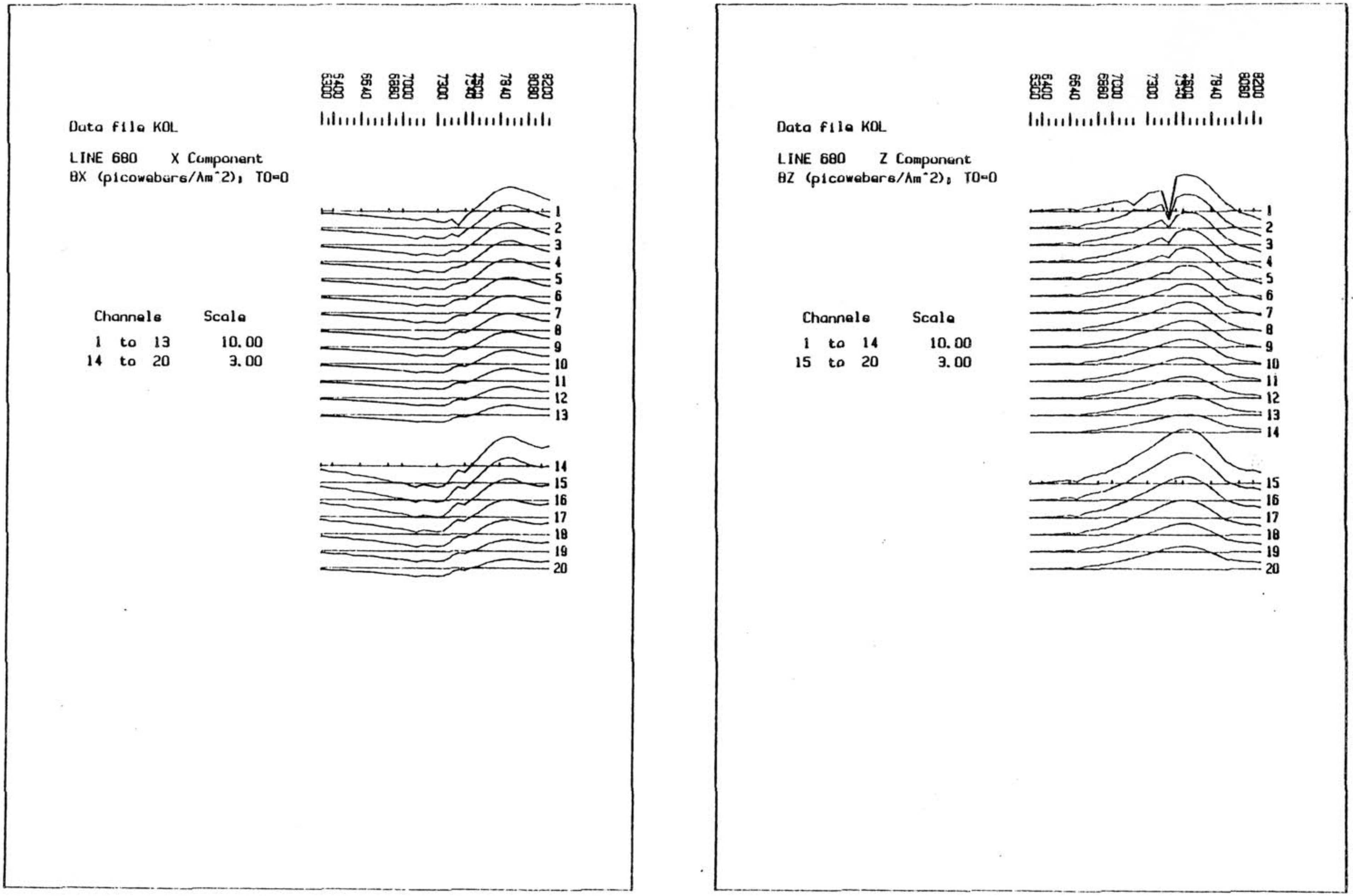
dBX/dT (nV/Am^2); T0=0
Channels Scale
1 to 2 100.00
3 to 7 10.00
8 to 11 3.00
12 to 16 1.00
17 to 20 .30
6300
6400
6640
6880
7000
7300
7540
7600
7840
8080
8200
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
Data file KOL
LINE 680 Z Component
dBZ/dT (nV/Am^2); T0=0
Channels Scale
1 to 3 300.00
4 to 6 30.00
7 to 9 10.00
10 to 14 3.00
15 to 20 1.00

Figure 9.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LINE 680 X Component
BX (picowebers/Am^2), T0=0
Channels Scale
1 to 13 10.00
14 to 20 3.00
6300
6400
6640
6880
7000
7300
7540
7600
7840
8080
8200
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
Data file KOL
LINE 680 Z Component
BZ (picowebers/Am^2), T0=0
Channels Scale
1 to 14 10.00
15 to 20 3.00
6300
6400
6640
6880
7000
7300
7540
7600
7840
8080
8200
1
2
3
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11
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14
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16
17
18
19
20

Figure 10.

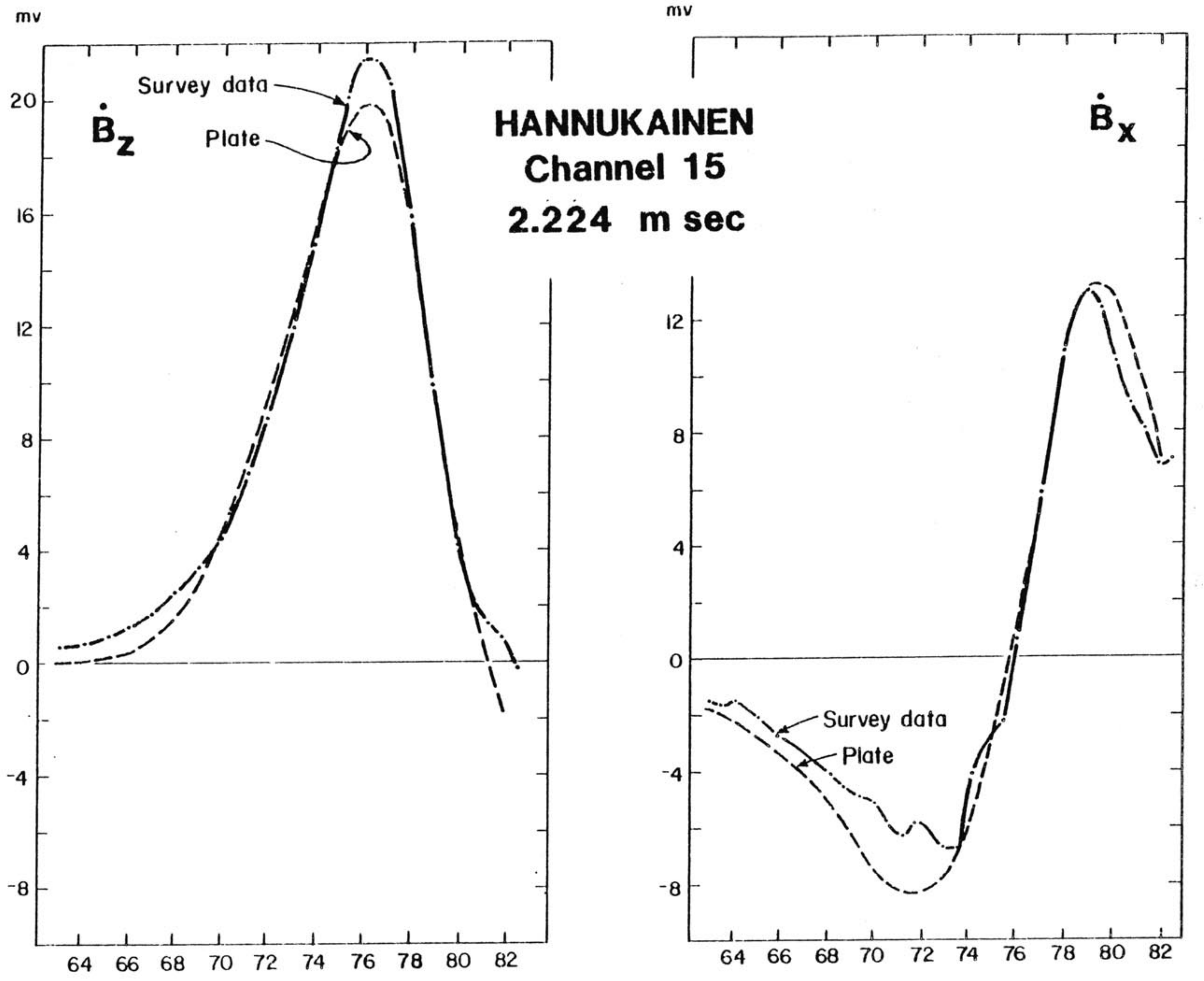

mv
20
16
12
8
4
0
-4
-8
$\dot{B}_z$
Survey data
Plate
64
66
68
70
72
74
76
78
80
82
HANNUKAINEN
Channel 15
2.224 m sec
mv
12
8
4
0
-4
-8
$\dot{B}_x$
Survey data
Plate
64
66
68
70
72
74
76
78
80
82

Figure 11.

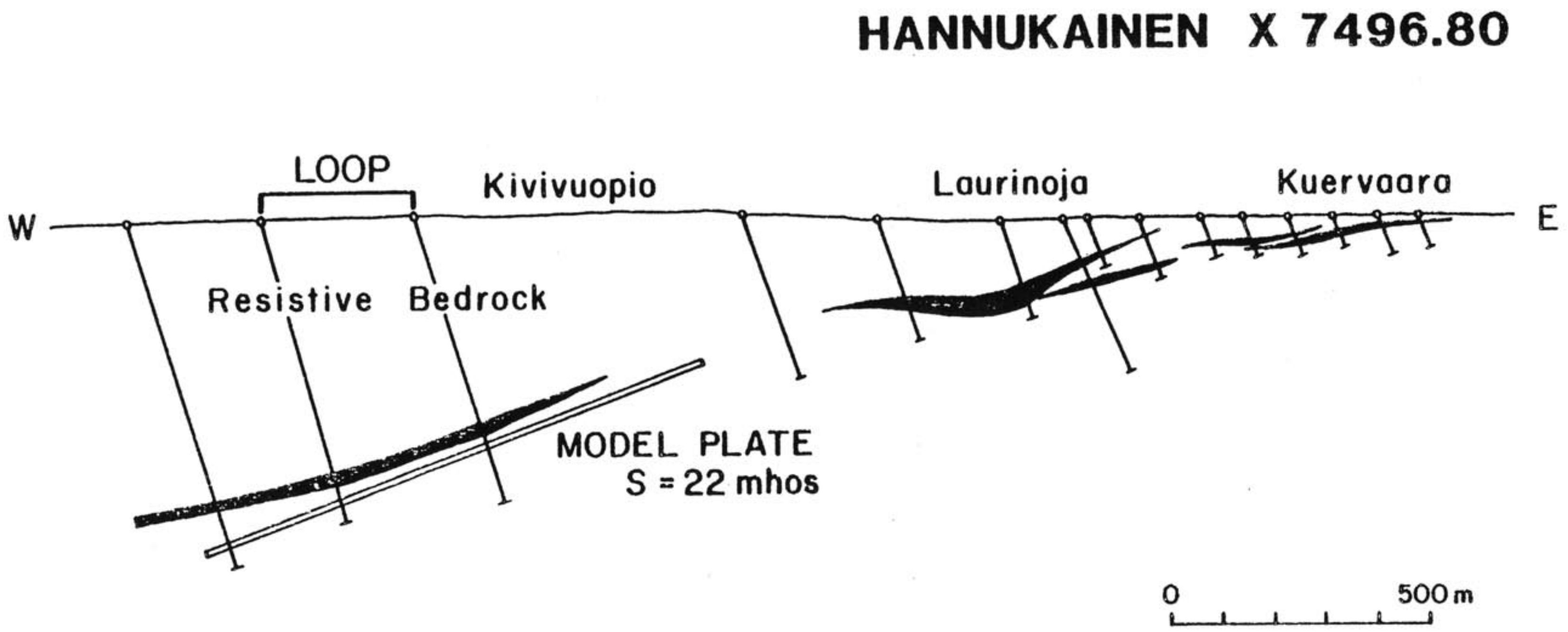

HANNUKAINEN X 7496.80
LOOP
Kivivuopio
Laurinoja
Kuervaara
W
E
Resistive Bedrock
MODEL PLATE
S = 22 mhos
0
500 m

Figure 12.

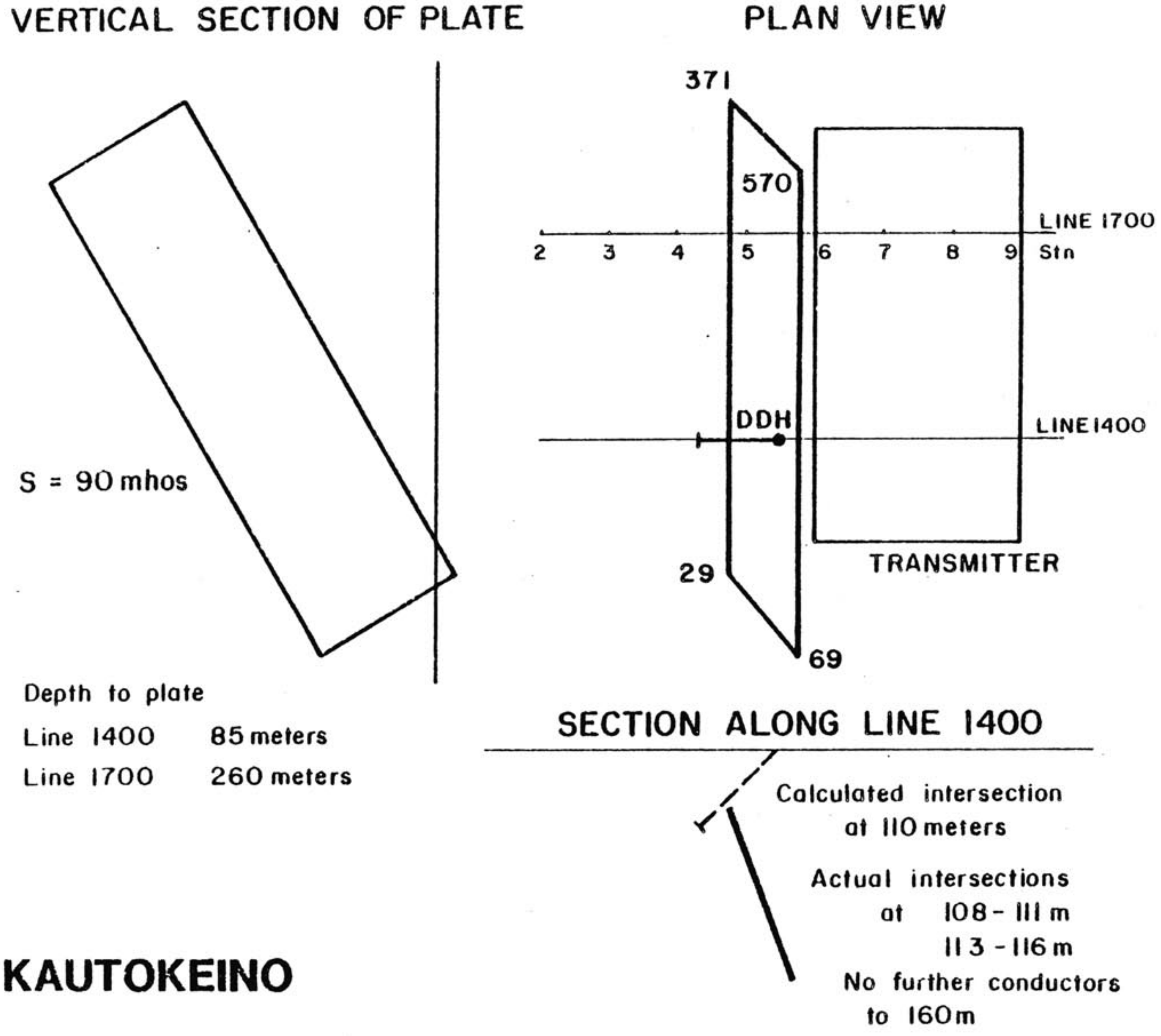
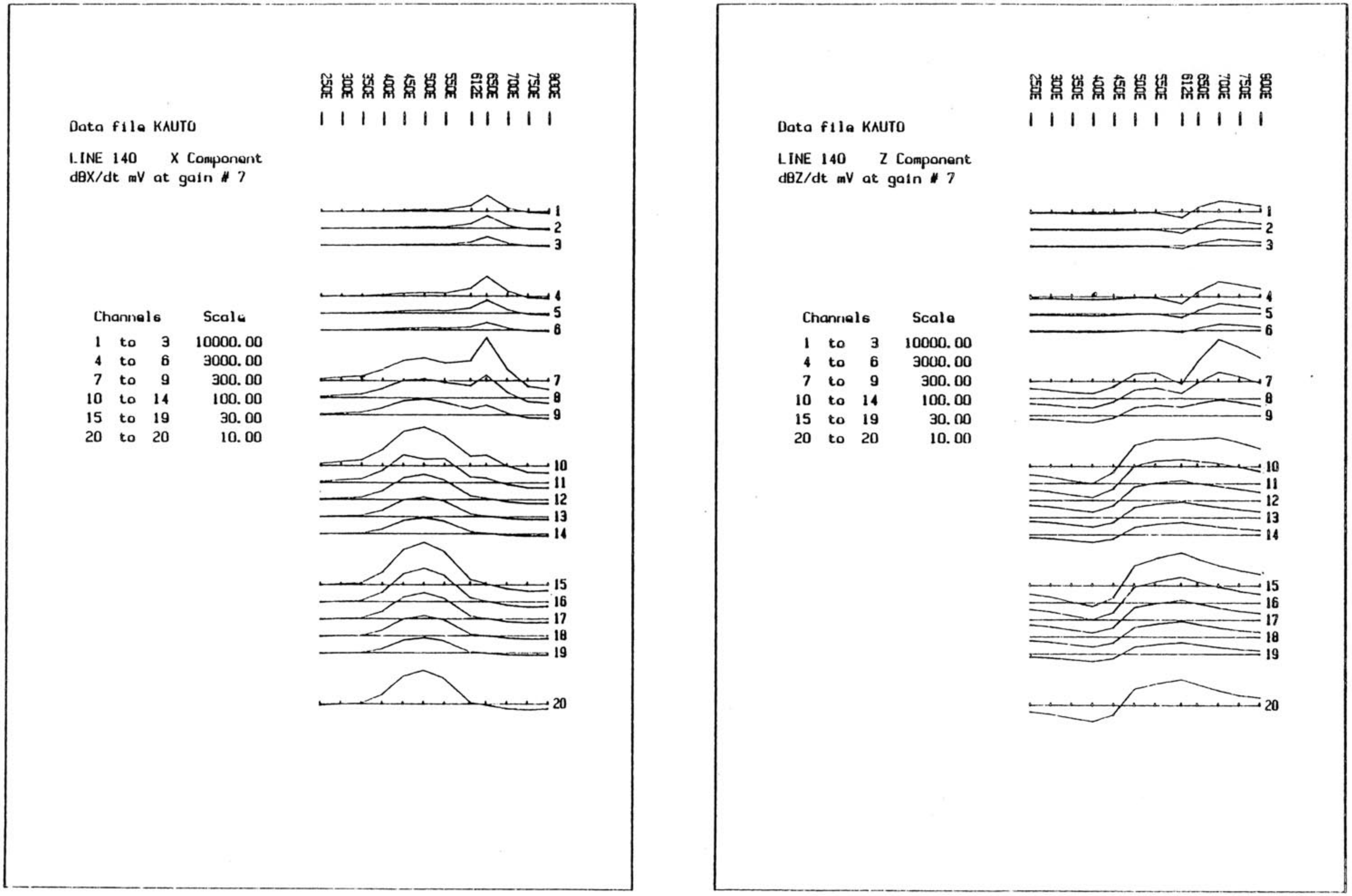

VERTICAL SECTION OF PLATE
S = 90 mhos
Depth to plate
Line 1400 85 meters
Line 1700 260 meters
KAUTOKEINO
PLAN VIEW
371
570
29
69
LINE 1700
2
3
4
5
6
7
8
9
Stn
DDH
LINE 1400
TRANSMITTER
SECTION ALONG LINE 1400
Calculated intersection
at 110 meters
Actual intersections
at 108 - 111 m
113 - 116 m
No further conductors
to 160m

Figure 13.



Data file KAUTO

LINE 140 X Component
dBX/dt mV at gain # 7

Channels			Scale
1	to	3	10000.00
4	to	6	3000.00
7	to	9	300.00
10	to	14	100.00
15	to	19	30.00
20	to	20	10.00

Data file KAUTO

LINE 140 Z Component
dBZ/dt mV at gain # 7

Channels			Scale
1	to	3	10000.00
4	to	6	3000.00
7	to	9	300.00
10	to	14	100.00
15	to	19	30.00
20	to	20	10.00

Figure 14.

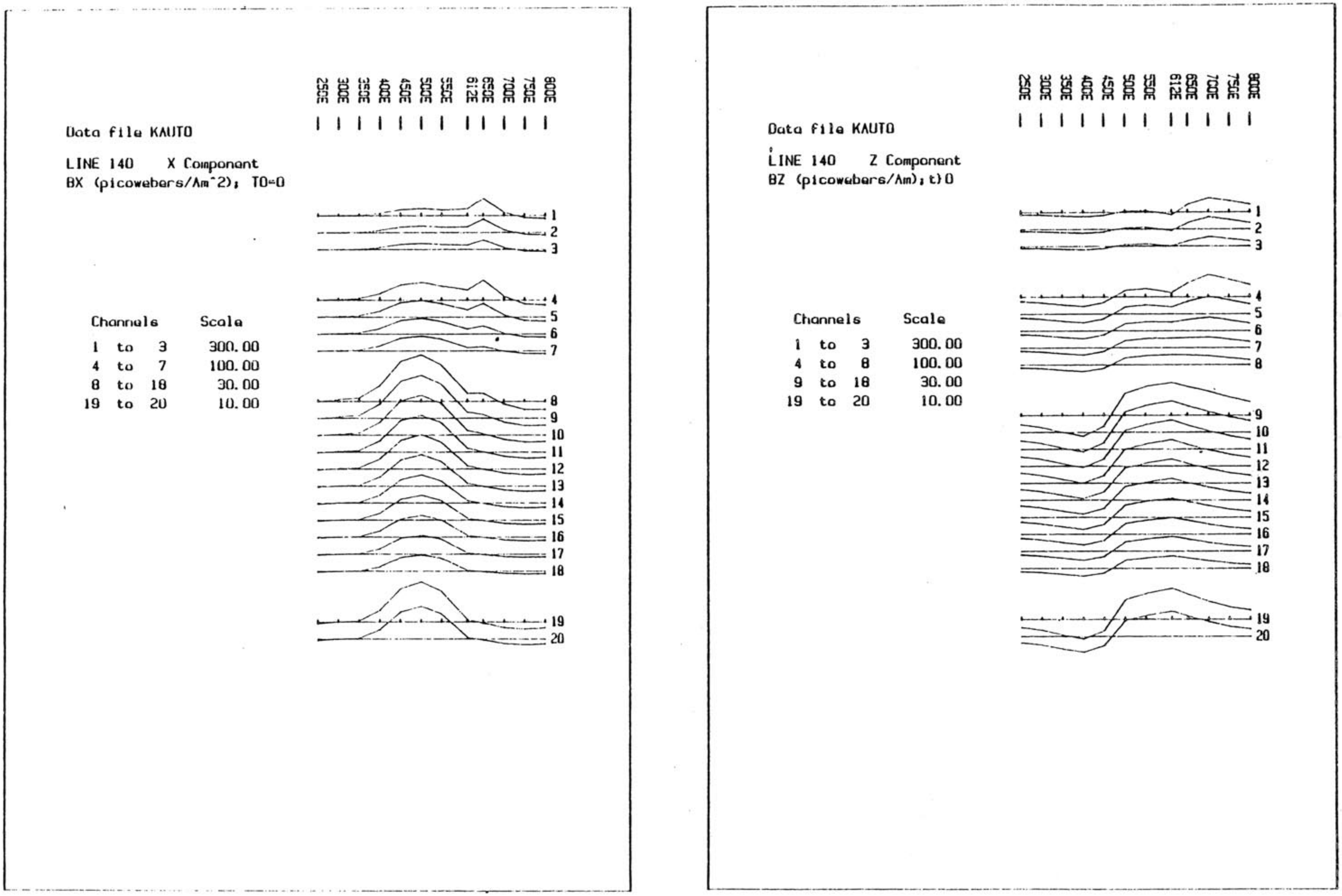
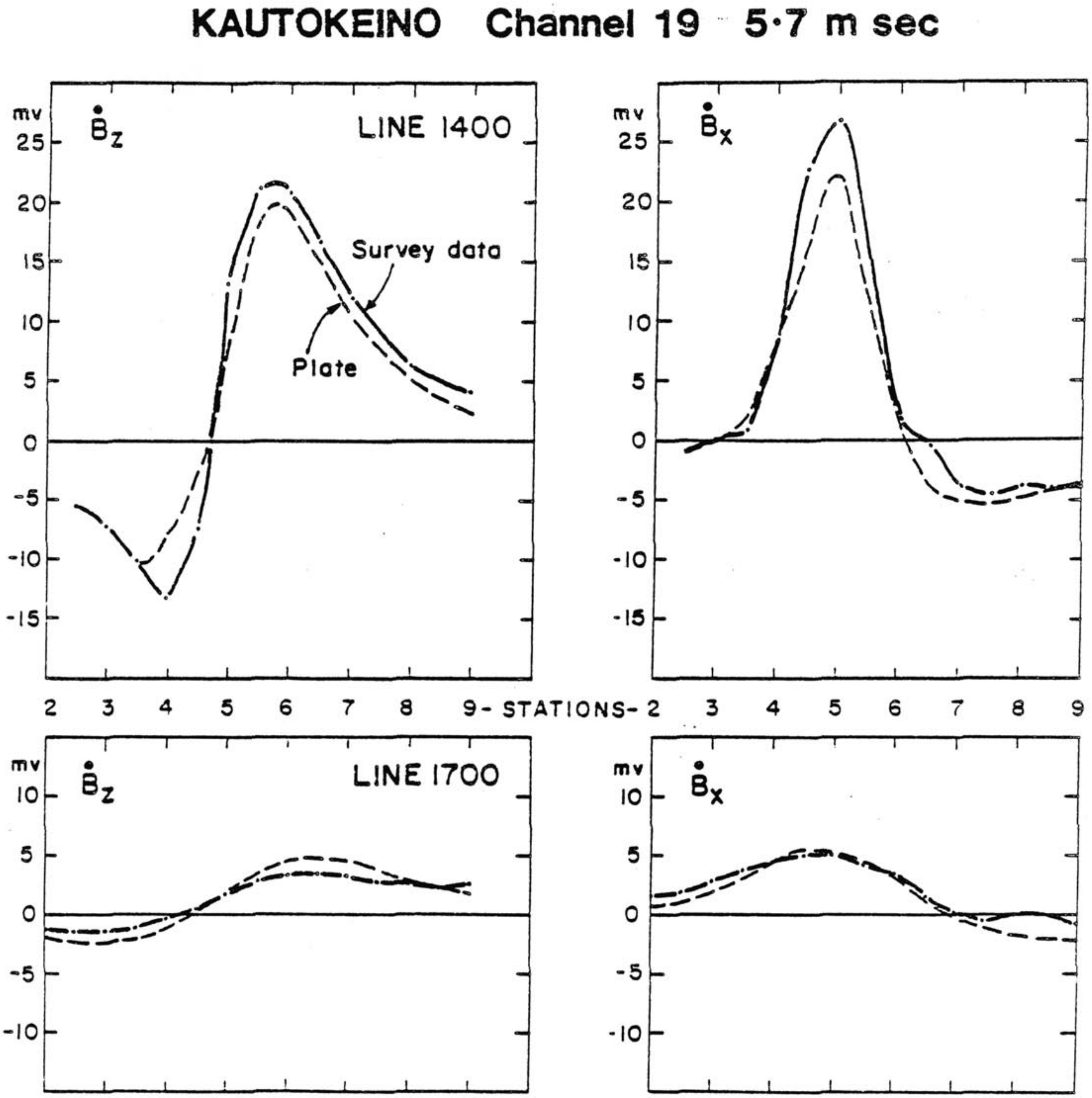

Data file KAUTO
LINE 140 X Component
BX (picowebers/Am^2); TO=0
Channels Scale
1 to 3 300.00
4 to 7 100.00
8 to 18 30.00
19 to 20 10.00
250E
300E
350E
400E
450E
500E
550E
612E
650E
700E
750E
800E
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
Data file KAUTO
LINE 140 Z Component
BZ (picowebers/Am); t)0
Channels Scale
1 to 3 300.00
4 to 8 100.00
9 to 18 30.00
19 to 20 10.00

Figure 15.



KAUTOKEINO Channel 19 5·7 m sec

Figure 16.