Time-lapse airborne EM surveys across a municipal landfill

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ABSTRACT

In contrast to the majority of historical landfills, modern municipal landfills are highly engineered and follow a contain and seal strategy of leachate management. The purpose of the management system is to render the waste products inert and environmentally safe. A requirement for monitoring and assessment of the installation on the scale of decades is a consequence of the strategy. Data obtained from two repeated fixed-wing airborne electromagnetic surveys across an active, municipal solid waste landfill are considered here. The time interval between the surveys is 4 years. In theory such data may be used to both test the isolation performance of the installation and to monitor mass (leachate) transport behaviour within the landfill structure. Single frequency (3.1 kHz) data obtained at a similar density (100 m flight line spacing) over the 4 year span are presented and compared. These data have an expected mean depth of investigation of about 15 m within the landfill. Half-space conductivity models are determined from the survey data by an inversion procedure. Conductivities within the landfill are observed to be three orders of magnitude above background. From the initial survey data, a specific distribution of high conductivity material can be identified in three of the landfill cells (peak values of 170 mS/m). Four years later, a considerable redistribution of material is apparent in the results obtained across two of the cells (peak values of 317 mS/m). A third cell shows no change. A subtraction of the two time-lapse conductivity models allows the dynamic components of the conductivity distribution (all increases with time) to be mapped within individual cells. All larger conductivity increases (e.g. > 20 mS/m) are confined to the operational landfill.

Introduction

Landfill sites can be considered as artificial hydrogeological systems in which leachate and gas is generated. Environmental geophysical surveys have developed a strong track record in the field of waste-site assessment and characterisation. It is probable that all known geophysical methods have been applied to one, or more, of the large number of technical issues that arise in the landfill context. The vast majority of landfills are historical or legacy sites used/operated prior to regulatory frameworks. Within the modern context three general classes of landfill can be identified: (a) Dilute and disperse. Wastes are buried with little attention to leachate/gas generation. Many 'legacy' sites fall into this category, (b) Contain and seal. Modern sites in which wastes are buried with a great deal of attention to leachate/gas generation, isolation and containment, (c) Reactor (or bioreactor) landfill. Waste degradation is accelerated to enhance biogas production for energy applications.

Modern licensed sites, usually following regulatory requirements, are highly engineered and follow the contain and seal strategy of leachate management (Mather, 1995). The purpose of the waste management system is to render the stored waste products inert and environmentally safe. Although the degree to which the technological solution is sustainable in the long term can be debated (Allen, 2001), a requirement for monitoring on the scale of decades, or longer, is an inevitable consequence of the strategy.

Geophysical surveys may be used in initial site characterisation to aid the planning of modern landfill locations (Bernstone & Dahlin, 1999). One of the more common applications is, however, the monitoring of possible leakage of leachate materials from an existing landfill. Many of any the geophysical studies reported in the literature have been undertaken on unregulated, often inactive, 'legacy' landfill sites (e.g. Greenhouse et al., 1983; Lanz et al., 1998). In the geophysical assessment of former landfills, one of the clearest associations is that between high electrical conductivity and accumulations of waste leachate. Limited tabulations of the conductivity of landfill material containing leachate (e.g. Whitley and Jewell, 1992) indicate maximum in-situ values of between 100 and >650 mS/m. Meju (2000) further discusses the relationships between landfill electrical conductivity and simple leachate parameters such as total dissolved solids (TDS) and chloride content. When, as here, a modern engineered and contained landfill is considered, the same argument applies i.e. it is assumed that bulk subsurface conductivities, determined geophysically, can act as a surrogate for the characterisation of leachate generation and accumulation.

The transport of leachate through a confined landfill depends on a number of factors including the degree of waste compaction and variations in the natural and artificial water/fluid flow through the system. The transport can be slow, non-uniform and sometimes discontinuous (Fang, 1995). In terms of the regulatory framework, a form of lifetime prediction and monitoring of mass transport phenomena needs to be undertaken (e.g. Qian et al., 2002). In order to monitor both leachate levels and the internal dynamics of leachate behaviour, appropriate geophysical measurements can be periodically undertaken. Two of the main difficulties in the application of geophysics to modern landfills are both the scale of the multi-cell operation and the fact that they are likely to be operational and hazardous. In these circumstances, airborne electromagnetic systems may be usefully employed.

In the present study time-lapse airborne electromagnetic (AEM) results across a large, modern Municipal Solid Waste (MSW) landfill near Helsinki are described. The results were obtained across a 4 year baseline between 1993 and 1997. The objective of the study is to describe the type of performance that may be expected of AEM methods in relation to the long-term monitoring of large, active contain and seal landfills.

The airborne EM technique

Frequency-domain AEM systems, discussed here, exist as towed-bird configurations (typically Helicopter HEM systems) and as fixed-wing (wing-tip sensor) configurations. Typically HEM operates the towed sensor bird about 30 m above ground level while fixed wing systems (with larger dipole moments) may be flown much higher. Holladay and Lo (1997) provide a thorough review of frequency-domain AEM systems and their applications.

The Twin-Otter survey aircraft (Figure 1) operated by the Geological Survey of Finland (GTK) routinely acquires magnetic gradiometer (wing tip), radiometric (gamma radiation) and dual frequency EM data (Poikonen et al., 1998). Jokinen and Lanne (1996) describe the application of the system to the mapping of contaminant plumes from landfills in Finland. Beamish (2002a) describes environmental applications of the system in the UK. The EM coupling ratios (between vertical transmitter and receiver coplanar coils) at two frequencies (3.1 and 14.4 kHz) are recorded simultaneously at 4 Hz. Coupling ratios are here defined as the secondary to primary field ratio multiplied by 10^6 for both the in-phase and in-quadrature components. Sampling along the flight direction is typically between 10 and 15 m for flight speeds of about 200 km/hour. A radar altimeter provides elevation information.

EM induction by elevated magnetic dipoles is governed both by the frequencies used and by the geometrical attributes of the system, especially flight altitude. The electromagnetic footprint of the system on the ground determines the lateral scale of the measurement. In order to visualise the scale of an AEM measurement we have calculated the induced current distribution in a uniform half-space using parameters appropriate to the present investigation. The conductivity is taken to be 0.1 mS/m (10000 ohm.m) and the flight altitude is 30 m. A vertical coil transmitter operating at 3.1 kHz produces the current distribution at the ground surface contoured in Figure 2. The distribution is asymmetric and is elongate perpendicular to the flight direction (y direction). The maximum current is produced directly beneath the transmitter coil and decays laterally as shown by the contours. The decay, or attenuation, of induced electric fields is usually described in terms of skin-depth, which is defined as the length over which the amplitude decays by 1/e (i.e. 37%). The region contoured in Figure 2 defines 3 skin-depths and the inner infilled region defines 1 skin-depth from the central maximum. The inner region defines the principal zone of the subsurface assessment using the AEM method (for the parameters considered). The zone is some 96 m wide perpendicular to the flight direction and about 40 m in width along the flight direction. Each measurement will provide a subsurface volumetric average of bulk conductivity over an area in excess of 3500 m^2.

The depth of investigation in AEM is both frequency and conductivity dependent; it is also a function of survey altitude. Centroid depths for the GTK system, which are a measure of the mean-depth of induced currents, are discussed by Beamish (2000b). For the lower frequency data considered here, centroid depths will be about 15 m in the conductive (100 mS/m) environment of the landfill and will increase to over 50 m as the conductivity reduces to values less than 10 mS/m.

The interpretation of AEM data proceeds using one dimensional (1D) resistivity models. Common procedures largely developed and described by Fraser (1978) comprise the modelling of the observed coupling ratios by a pseudo-layer algorithm. The algorithm provides dual interpretation parameters (apparent resistivity and apparent depth) at each frequency. Formal (non-linear, least-squares) inversion of AEM data is becoming more widespread (Sengpiel and Siemon, 2000) and a multi-layer inversion (Beamish, 2002b), restricted to a half-space assessment, is used here to provide models of the subsurface resistivity distribution.

The Ämmässuo Landfill

The Ämmässuo landfill is a Municipal Solid Waste (MSW) facility situated in the Espoo district to the west of Helsinki in southern Finland. The facility is the largest landfill in Finland with a capacity of 10 million cubic metres and a total area of some 150 hectares. With an extension, now under construction, it is expected to operate up to the year 2030.

The landfill is built on bedrock. In an area of approximately 20 hectares, where the rock was fragmented, a 2 mm geotextile was installed to protect groundwater. All leachate and run off waters in the landfill area are channelled through drains and are pumped over 6 km to a sewage works for treatment. There is no leachate recirculation. Operation of the multi-cell landfill began in 1987. Ground and surface water chemistry is routinely monitored at the site and thus far there is no indication of groundwater contamination. Ground-based electrical and electromagnetic geophysical investigations have been conducted just to the south of the landfill zone and are described by Vanhalla et al. (2000).

An aerial photograph of the landfill is shown in Figure 3 looking from South to North. Three contiguous and active cells can be identified in the central area and are labelled 1, 2 and 3. Cell 4, in the east, is an area reserved for biological waste. In the south (main foreground of Figure 3) is a large Cell, labelled 5, which was inactive (i.e. undergoing construction), during the survey period discussed here. Figure 4 shows the cell structure at the landfill in plan view across a 3 x 2.5 km area. The Turku motorway traverses the NE corner of the area and is indicated. The N-S dotted lines are the 1997 survey flight lines, which are discussed below.

The bedrock at the site comprises non-magnetic, granitic basement typical of the Fenno-Scandinavian shield. In electrical terms the bedrock is highly resistive (i.e. in excess of 10,000 ohm.m). This means that any anthropogenic influences, such as those comprising conductive leachates, will offer a high level of electrical contrast with the 'background' host material.

The area of the landfill had been mapped using airborne geophysics as part of the Finnish national airborne mapping programme in 1984, before the operation of the landfill began. The 1984 measurements were made using a 200 m N-S line spacing (Jokinen and Lanne, 1996). At the end of 1993 the area was resurveyed in the same north-south direction but using a denser (100 m) line spacing. The flight lines were about 5 km in length and flight altitude varied between 25 and 35 metres. Jokinen and Lanne (1996) discuss differences in the magnetic and radiometric data between 1984 and 1993. In 1993, the airborne EM system operated at only one frequency (3.1 kHz). In 1995, the Geological Survey of Finland improved the AEM system by adding a new higher frequency channel to the existing equipment. As a consequence, when the area was resurveyed in 1997, EM data comprised two frequencies (3.1 and 14.4 kHz). The 1997 survey again used 100 m, N-S flight lines as shown in Figure 4.

The lower frequency EM data obtained in 1993 and 1997 provide two equivalent AEM surveys over a 4 year time span and these form the basis of the present study. A standard area of 3 x 2.5 km, centred on the landfill, is used for the presentation of results.

The AEM survey data

Airborne EM data comprise in-phase (P) and in-quadrature (Q) components (coupling ratios in ppm) at each operational frequency. Such 'raw' data can be used, initially, to form simple anomaly maps. Conductive features provide higher values in the coupling ratios. Figure 5 shows the in-quadrature component data for the 1993 and 1997 surveys contoured at the same scale. The in-phase data show a similar, though not identical, response pattern. The maximum values in the in-quadrature data are 19000 ppm in 1993 and they increase to 28000 ppm in 1997. The resistive nature of the surrounding bedrock produces only small coupling ratios (< 1000 ppm).

In Figure 5, the cell structure of the landfill is shown by the shaded polygons. Only one anomaly (> 2000 ppm) occurs outside the landfill, to the north. The anomaly trebles in magnitude, from 2000 to 6000 ppm between 1993 and 1997 and also increases in size. The cause of the anomaly is thought to be 'stockpiled' conductive clays (i.e. stripped overburden) generated by the construction industry.

The 1993 data (Figure 5a) display patterns within the operational cell structure of the landfill. Two main peaks occur along the western margin of Cell 1 and a further smaller amplitude peak occurs in the south east. Single anomalies are associated with Cell 2 (in the centre of the cell) and Cell 3. Comparing these data with those from 1997 (Figure 5b) clear differences emerge. In Cell 1 the dual western margin anomalies remain but a large amplitude centre has appeared towards the south. In Cells 2 and 3 the two single anomalies remain but are reduced in amplitude and are more diffuse. In both 1993 and 1997, no anomalies (> 2000 ppm) are observed in Cell 4 which defines the biowaste area.

Conductivity models

The values of the raw coupling ratios depend on the altitude of the aircraft and this inevitably varies during each survey but is recorded by a radar altimeter. In order to remove the dependence of the response on survey altitude it is necessary to construct a conductivity model of the subsurface. Conventional, industry-standard, techniques involve fitting a uniform half-space model of conductivity at each observational frequency (Fraser, 1978). Here we use a formal, iterative least-squares inversion solution to provide a half-space conductivity model using the two data components together with recorded altitude (Beamish, 2002b). The procedure provides a conductivity model at each observational point together with a measure of misfit between the model and the data.

As an example, the data along a single survey line (Line 522, Figure 4) are used to illustrate the modelling procedure. The flight line traverses Cells 2 and 3. The measured in-phase (P) and in-quadrature(Q) data are shown as symbols using a logarithmic scale in Figures 6a and 6b, respectively. For each measured pair of data, the inversion procedure returns a conductivity model, shown in Figure 6c. The continuous lines show the response of this model in Figures 6a,b. A comparison of the observed and modelled responses indicates the extent to which the model can be considered adequate.

The minimum noise level of the data is expected to be of the order of 10 ppm or less (Poikonen et al., 1998). This figure may increase towards 100 ppm when other sources of error (e.g. calibration and levelling) are allowed for. The observed coupling ratios extend over 4 orders of magnitude and the in-phase (P) results exhibit the greatest degree of misfit between model and data. In the south of the profile, the highly resistive bedrock produces very small coupling ratios and it is unlikely that the data can discriminate conductivities of less than 0.1 mS/m. The highly conductive nature of the landfill zone produces very rapid spatial gradients in both the response and the conductivity model. Both undergo increases of several orders of magnitude over a few hundred metres. To the north of the conductive landfill zone, conductivities are 1 mS/m and less and adequately modelled spatial variations are observed.

The conductivity models obtained for the whole survey area are shown in Figure 7a(1993) and 7b (1997) using the same contour scale. The maximum conductivities are 170 mS/m (1993, Figure 7a) and 317 mS/m (1997, Figure 7b). Conductivities in excess of 20 mS/m are confined to the landfill. In order to demonstrate some of the lower level of conductivity variations, the interval between 2.5 and 20 mS/m is shown as a cross-hatched contour interval. This contour interval delineates growth in the extent of the 'sewage' anomaly to the north of the landfill and in the anomaly associated with the highway.

Although broadly similar, significant differences exist between the in-quadrature component anomaly patterns of Figure 5 and the conductivity model contours of Figure 7. The conductivity model is considered more reliable since it takes into account both in-phase and in-quadrature components together with altitude. The 1993 data (Figure 7a) display patterns within the operational cell structure of the landfill. A single broad peak occurs along the northern and west margin of Cell 1 and a further less conductive peak occurs in the south east. A dual peaked conductivity anomaly is associated with Cell 2 while Cell 3 contains a single anomaly. Comparing these data with those from 1997 (Figure 7b) clear differences emerge. In Cell 1 a broader and much more conductive anomaly has developed and now covers the majority of the cell. Within Cell 1, two conductivity centres can be discerned. In Cell 2 a more intense dual peaked anomaly is observed. By way of contrast, the conductivity anomaly associated with Cell 3 is little changed over the four year period. In both 1993 and 1997, no anomalous conductivities are observed in the eastern biowaste area (Cell 4).

Conductivity increases 1993-1997

Given the two standardised conductivity models shown in Figure 7, it is possible to subtract the two sets of results (i.e. subtract the 1993 model from the 1997 model) to arrive at a model distribution that describes the conductivity increase between 1993 and 1997. All significant conductivity differences, formed by the subtraction, are observed to be *increases*. The subtraction removes the static (time-independent) components from the data and examines the dynamic (time-dependent) components of the conductivity distribution. The conductivity difference model (1997-1993) is shown in Figure 8. The results can be used in conjunction with the actual values of 1993 and 1997, shown in the previous Figure, to arrive at an understanding of the dynamics of leachate behaviour in the landfill.

It is evident from Figure 8 that all the significant increases (e.g. greater than 20 mS/m) are confined to the operational landfill. Lower levels of conductivity increase (4 to 20 mS/m) are shown by the cross-hatched contour interval. Increases are associated with both the ‘sewage’ anomaly to the north of the landfill and the highway. Several elongate ‘fingers’ appear at the lower contour interval. Two fingers exist at the northern end of Cell 1 and a more extensive finger exists between Cells 3 and 4. All three of these increases are contained within the landfill (see Figure 3) and are likely to be due to at-surface operations.

First we take the 1993 conductivity model (Figure 7a) as a ‘baseline’ of the distribution of leachate concentration. We then assume that all leachate has the same high conductivity. Figure 8 then becomes a measure of the dynamics of leachate generation across the four year time period. It is evident that the main growth occurs in Cell 1 and moves from the perimeter towards the centre. In Cell 2, an existing two peak distribution migrates west and develops into a single concentration encompassing the majority of the cell. Although an existing concentration appears in Cell 3 in 1993, there appears to be no major change in leachate generation over the four year period. Clearly the results presented confirm that there is no geophysical evidence of significant lateral leakage from the operational landfill cells. The result is in accord with the regular monitoring of surface and groundwaters, which indicates that no groundwater contamination is present.

Summary and Conclusions

The present study has considered two repeated AEM geophysical surveys across a large, modern and active MSW facility. The time gap between the surveys was 4 years, which places it within one of the longer term time-lapse experiments considered in the geophysical literature. The AEM survey information relates to the bulk subsurface conductivities both within and in the vicinity of the landfill. One of the most straightforward applications of such data lies in the assessment of isolation and containment of the waste materials. It is apparent from the AEM results presented here and the ground monitoring systems that there is no indication of any significant leakage.

The analysis has been limited to a half-space conductivity assessment of single frequency data. The use of more frequencies across a wider bandwidth would permit a greater degree of vertical discrimination. It is estimated that the 3.1 kHz data examined here relate to the upper 15 m of the landfill materials. Within the limitations of the data and their analysis, valid models of the conductivity distribution were obtained. In the resistive bedrock of the Scandinavian shield, conductivities increase by over three orders of magnitude within the landfill.

It has been assumed that areas of highest conductivity within the cell structure of the landfill are likely to be associated with the major accumulations of leachate. In 1993, quite specific distributions can be identified within the three main cells. The

1993 data summarise the situation following 6 years of landfill operation. By 1997 a considerable redistribution had taken place in two of the Cells. The peak values in Cell 3 remained the same at about 100 mS/m. The subtraction of two equivalent time-lapse models allows the dynamic behaviour of the conductivity distribution to be determined. It is significant that all the differences were found to be increases over the four year period. The data qualities enabled conductivity increases to be mapped to a lower value of about 4 mS/m across the 3 x 2.5 km survey area. The interval from 4 to 20 mS/m defined small localised increases in zones associated with a sewage works and a motorway route. All larger (e.g. > 20 mS/m) increases were confined to the operational landfill. The conductivity increases shown in Figure 8 imply that major changes in mass transport and leachate generation occur and can be defined, within individual landfill cells, by the AEM method.

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References

Allan, A., 2001, Containment landfills: the myth of sustainability: Engineering Geology, **60**, 3-19.

Beamish, D. 2002a, Airborne EM applied to environmental geoscience in the UK: First Break, in press.

Beamish, D., 2002b, A study of conventional and formal inversion methods applied to high-resolution AEM data: Journal of Applied Geophysics, in press.

Bernstone, C. and Dahlin, T., 1999, Assessment of two automated resistivity data acquisition systems for landfill location surveys: two case studies. Journal of Environmental and Engineering Geophysics, **4**, 113-121.

Fang. H.Y. 1995, Engineering behaviour of urban refuse, compaction control and slope stability analysis of landfill: in: Sarsby, R.W., Ed., Waste Disposal by Landfill – Green'93. A.A. Balkema, Rotterdam, 427-431.

Fraser, D.C., 1978, Resistivity mapping with an airborne multicoil electromagnetic system: Geophysics, **43**, 144-172.

Holladay, S. and Lo, B., 1997, Airborne frequency-domain EM – Review and preview: in Gubins, A.G., Ed., Proceedings of Exploration 97: Fourth International Conference on Mineral Exploration, 505-514.

Jokinen, T., Lanne, E., 1996, Airborne geophysics in mapping contaminant plumes from landfills: Proceedings of SAGEEP '96, Keystone, Colorado, 981-995.

Lanz. E., Boerner, D.E., Maurer, H. and Green, A., 1998, Landfill delineation and characterisation using electrical, electromagnetic and magnetic methods: Journal of Environmental and Engineering Geophysics, **3**, 185-196.

Mather, J.D., 1995, Preventing groundwater pollution from land-filled waste – is engineered containment an acceptable solution: in: Nash, H., McCall, G.J.H., Eds, Groundwater Quality: Chapman & Hall, 191-195.

Meju, M.A., 2000, Geoelectrical invetsigation of old/abandoned, covered landfill sites in urban areas: model development with a genetic diagnosis approach: Journal of Applied Geophysics, **44**, 115-150.

Poikonen, A., Sulkanen, K, Oksama, M., Suppala, I., 1998, Novel dual frequency fixed wing airborne EM system of Geological Survey of Finland (GTK): Exploration Geophysics, **29**, 46-51.

Puranen, R., Säävuori, H., Sahala, L., Suppala, I., Mäkilä, M., Lerssi, J., 1999, Airborne electromagnetic mapping of surficial deposits in Finland: First Break, May, 145-154.

Qian, X., Koerner, R.M. and Gray, D.H., 2002. Geotechnical aspects of landfill design and construction: Prentice Hall Inc., New York.

Sengpiel, K.-P., Siemon, B., 2000, Advanced inversion methods for airborne electromagnetic exploration: Geophysics, **65**, 1983-1992.

Vanhala, H., Lohva, J., Lahti, M., Jokinen, T., Lehtimaka, J. and Seppo, E., 2000, An integrated geophysical study of grounwater monitoring system around a large landfill area: 62nd EAGE Conference and Technical Exhibition, Glasgow, UK. Expanded Abstracts, Vol. 1, A-47.

Whitley, R.J. and Jewell, C., 1992, Geophysical techniques in contaminated lands assessment: do they deliver?: Exploration Geophysics, **23**, 557-565.

Figure Captions

Figure 1. Twin-Otter geophysical survey aircraft operated by the Geological Survey of Finland showing the dual coil electromagnetic sensors on the wing-tips.

Figure 2. Modulus of the horizontal electric field at the surface of the Earth due to a horizontal magnetic dipole polarized in the y-direction. The source, located above the origin, has a dipole moment of 1 A/m, a frequency of 3 kHz and is 30 m above a 0.1 mS/m half-space. The results are plotted at a true scale using a logarithmic interval. Contoured region denotes 1 skin-distance (contours with infill) and 3 skin distances from the central maximum.

Figure 3. An arial view of the Ämmässuo MSW landfill site looking from south to north. Five cells are indicated with numbering.

Figure 4. Plan view of the Ämmässuo MSW landfill over a 3 x 2.5 km area. Five numbered polygons denote the main cell structure. Cell 4 is a biowaste area and Cell 5 was under construction at the time of the surveys. N-S flight lines (1997 survey) are shown. The location of flight line 522, referred to in the text, is indicated. M denotes the line of the motorway route.

Figure 5. In-quadrature (Q) coupling ratios (ppm) for (a) 1993 and (b) 1997 surveys. Values below 2000 ppm not shown. The contour interval is 4000 ppm. Polygons with heavy lines denote landfill cells.

Figure 6. Observations and model along N-S flight line 522. (a) In-phase data (symbol) and modelled response (line). (b) In-quadrature data (symbol) and modelled response (line). (c) Conductivity model (mS/m).

Figure 7. Contoured conductivity models for (a) 1993 and (b) 1997. The main contour interval is 40 mS/m. Polygons with heavy lines denote landfill cells.

Figure 8. Differences in the 1997-1993 conductivity models (1993 model subtracted from the 1997 model). The main contour interval is 40 mS/m. Polygons with heavy lines denote landfill cells.

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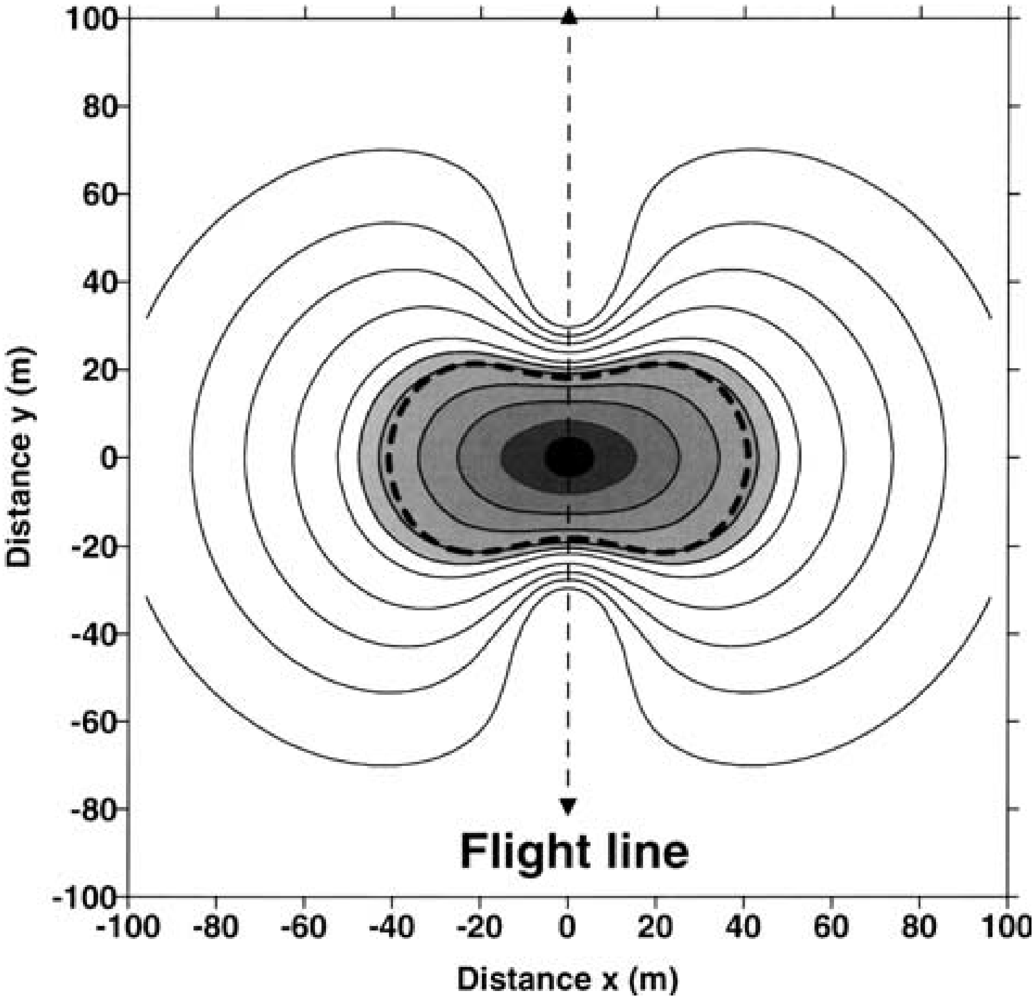

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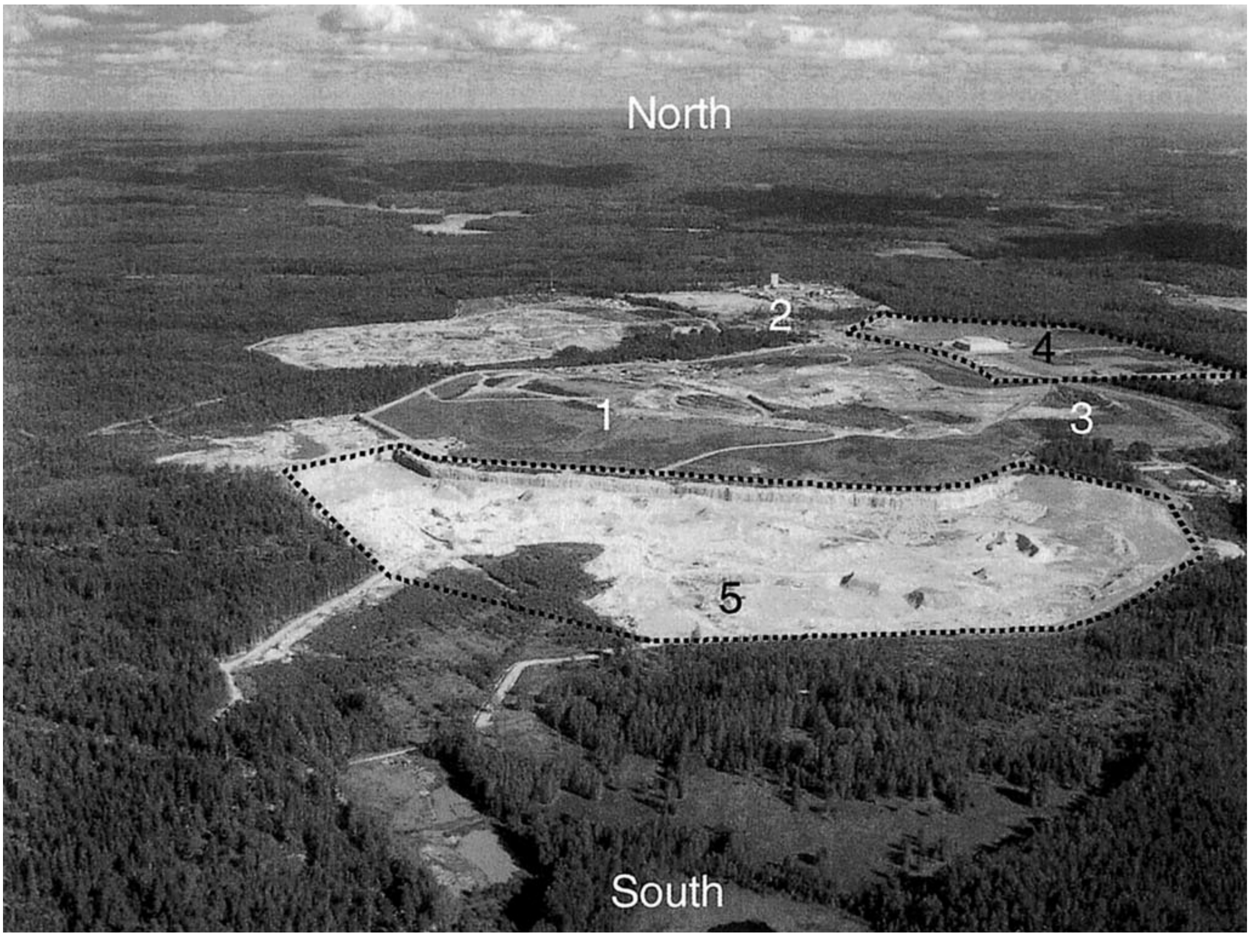

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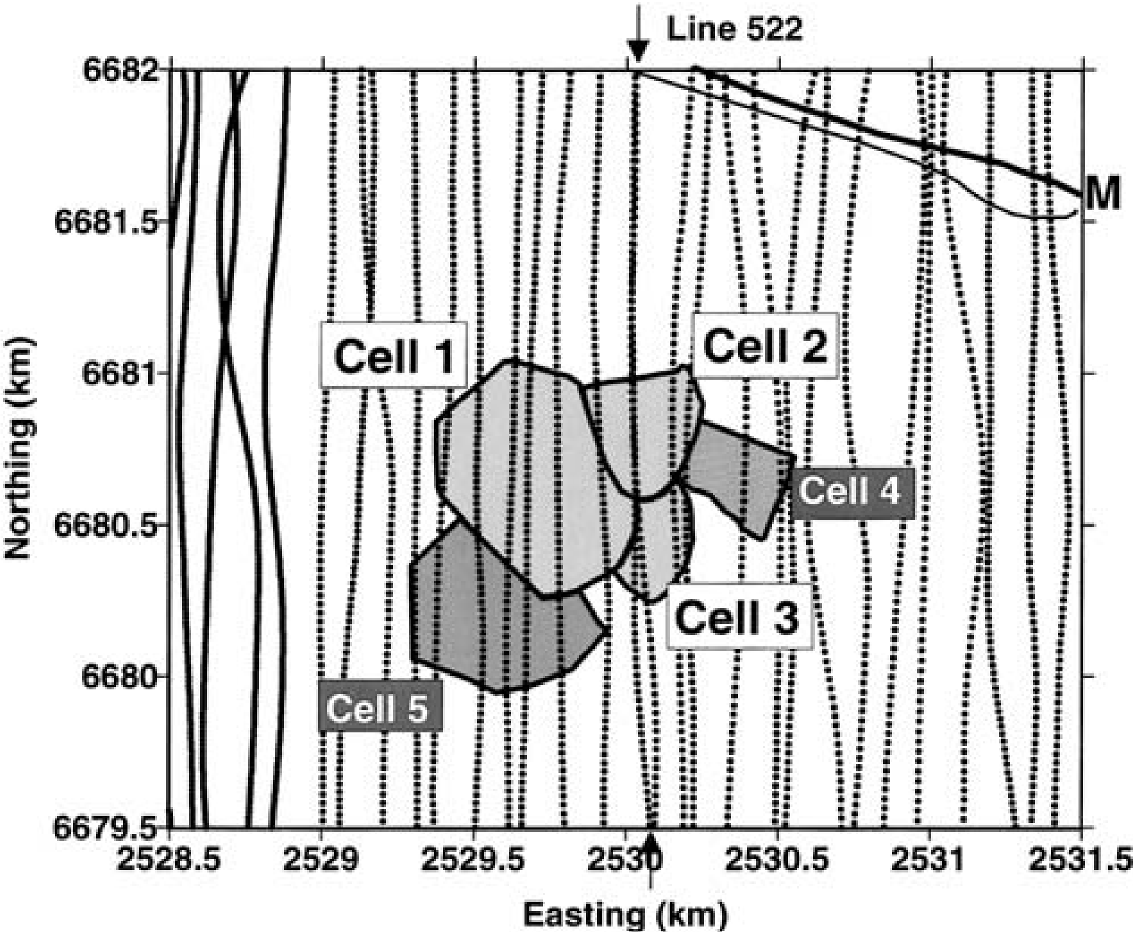

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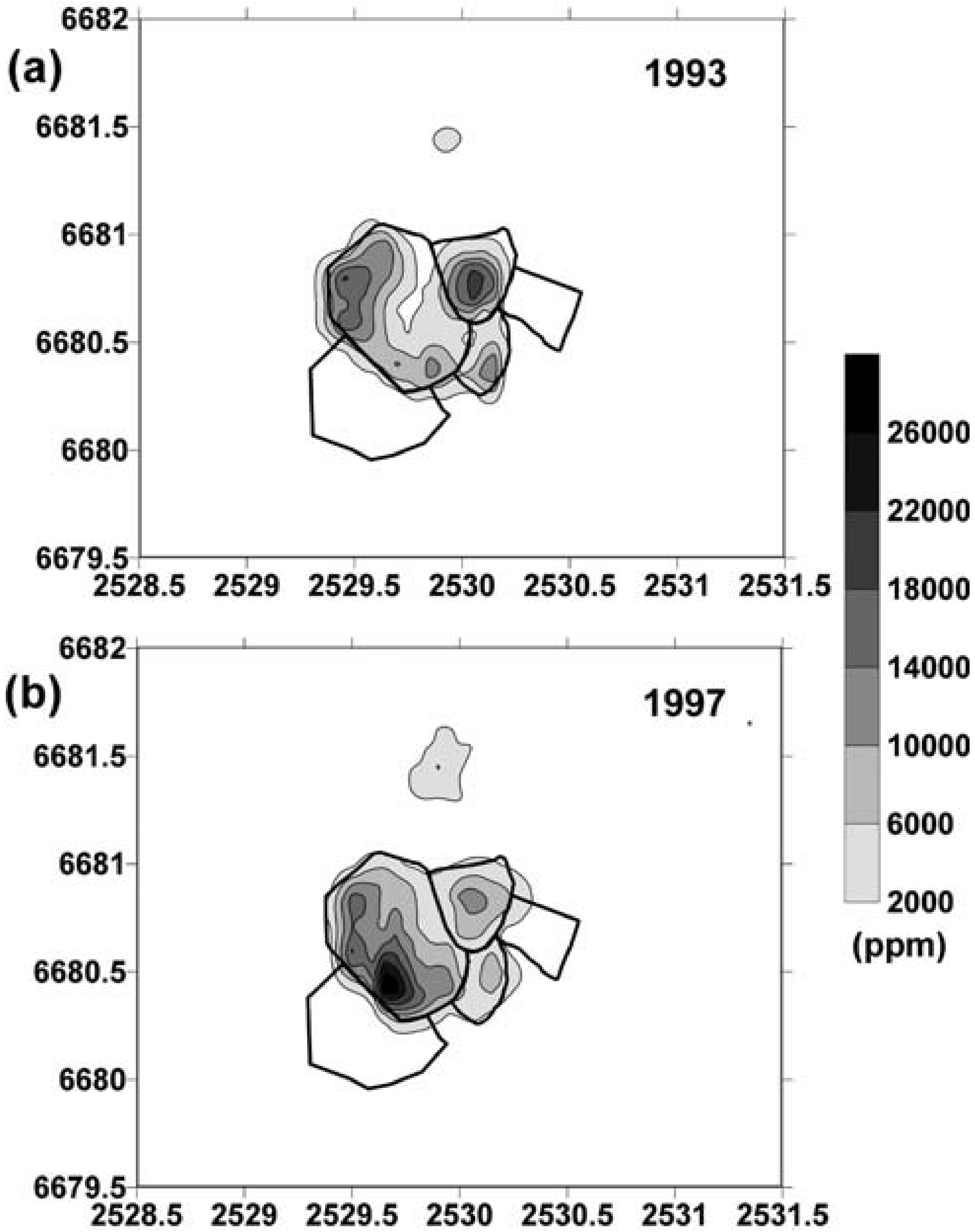

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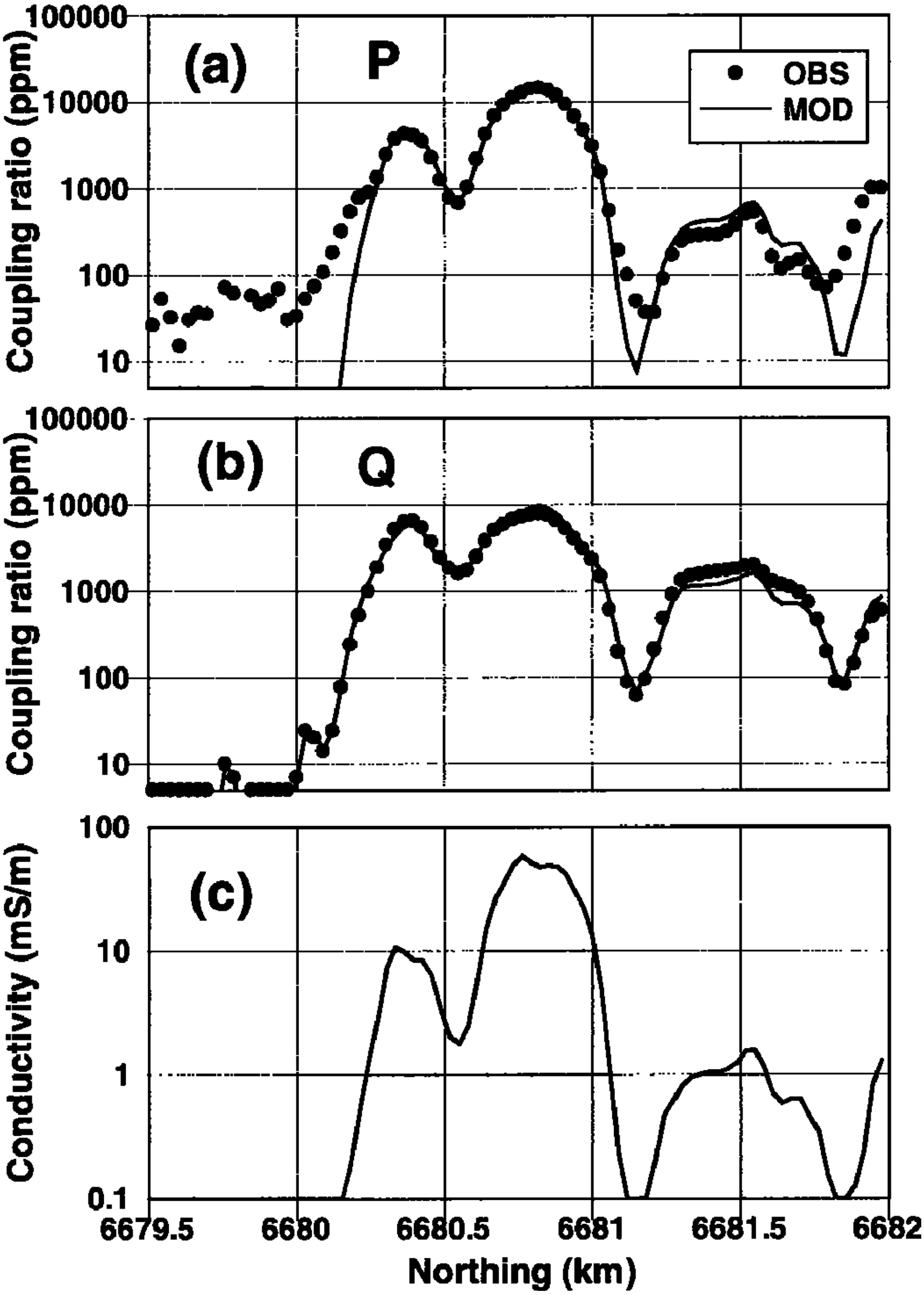

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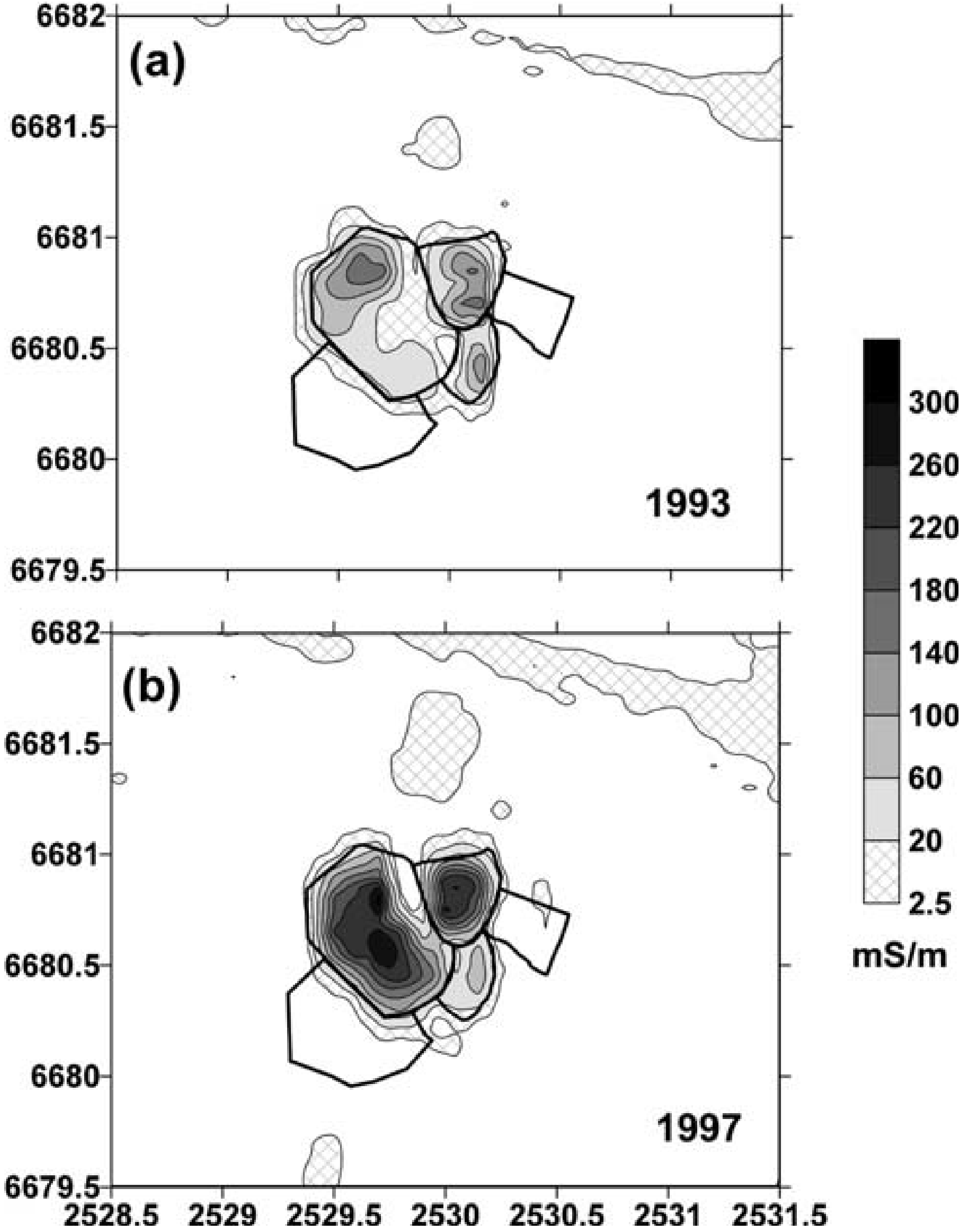

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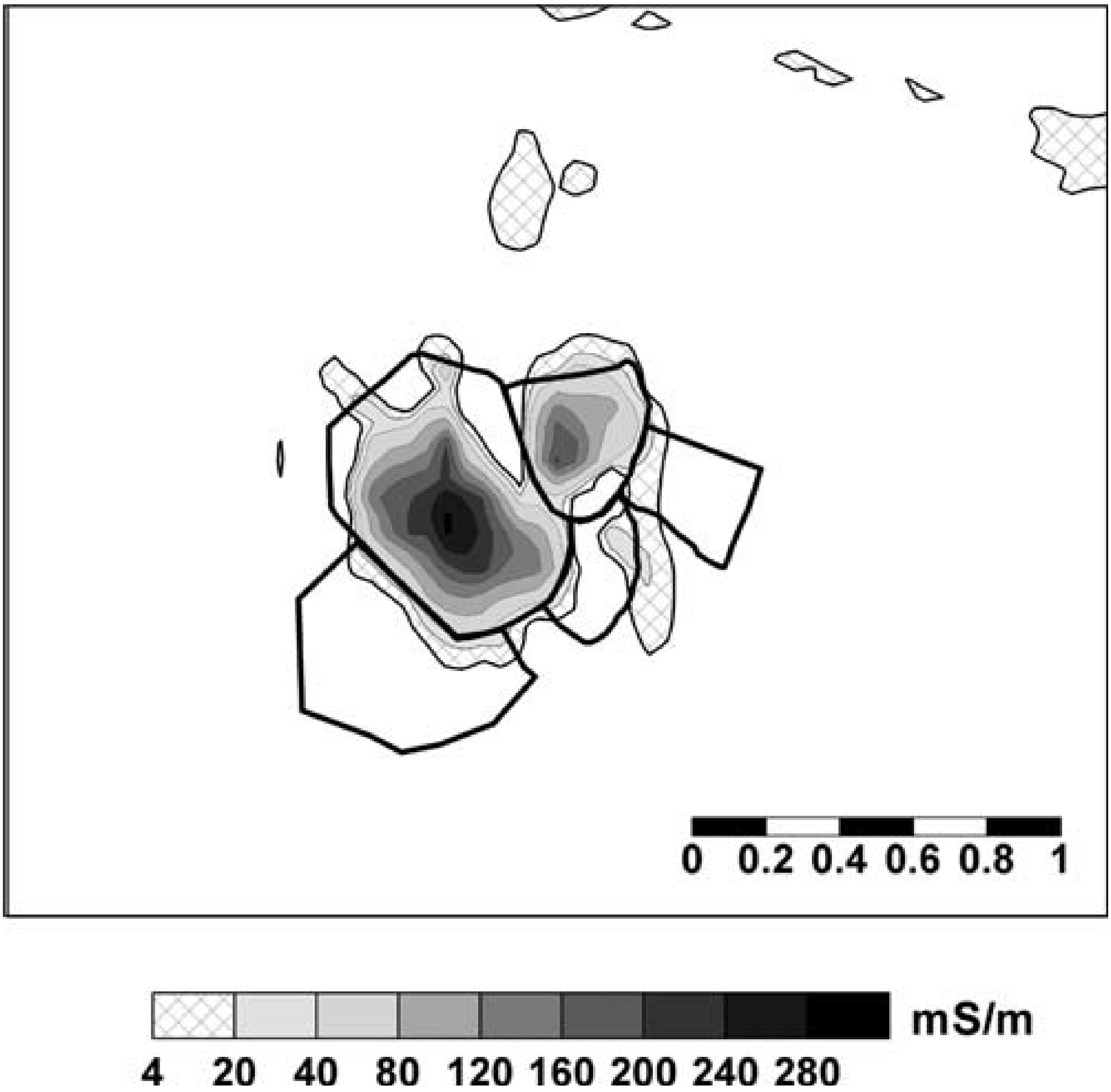

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