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Abstract

The regional deformation zone model for Forsmark will be expanded to include the catchment area for planned applications, that is within the "Site Descriptive Model – Safety Assessment Report" area, SDM-SAR.

An interpretation of lineaments, forming the base for further deformation zone modelling, has been carried out within a delimited work area including the catchment area, SDM-SAR.

The minimum surface trace length of the deformation zones is set to 5 km. However, the lineament interpretation is in accordance with previous similar work and thus has a minimum ground surface trace length of approximately 3 km.

Lineaments are determined by identification and outlining of vectors using visualization of the various magnetic, VLF and elevation datasets.

Interpretation of lineaments has been carried out in accordance with the methodology and strategy previously used in the Forsmark site modelling. In short, it is presumed that magnetic data is considered a more liable source for identifying deformation zones from mainly low magnetic lineaments. In this work the methodology include to identify, describe and document the spatial occurrence of magnetic lineaments in the first place. Existing topographic data and airborne geophysical VLF data are used as a support for identifying magnetic lineaments and for better tracing location and propagation of a magnetic lineament.

The magnetic lineaments identified are graded in low, medium and high uncertainty mainly with respect to the clarity in which they appear but also, in some cases, involving a judgement regarding the specific geological situation and the possible cause of the lineament. In this work, two major groups of magnetic lineaments are distinguished by their nature:

- Magnetic minima, discordant to geological and geophysical trends.
- Magnetic minima connection, concordant to geological and geophysical trends.

The lineament is described with attribute data in a table with the same content that has been used in previous work. Notable are attributes such as character, uncertainty, length and mean direction as well as in which data a lineament has been identified.

A weight attribute considers both the degree of uncertainty and the number of methods in which a lineament has been identified. The weight attribute assessment yields an indication of the confidence of a lineament.

The magnetic lineament segments initially identified (method specific/co-ordinated lineaments), were subsequently linked together into linked lineaments. At this stage, linked lineaments from previous work, model version 2.2, were also included.

From this work, in total 96 linked lineaments have been generated, to compare with 44 linked lineaments in previous regional model version 2.2, SDM-Forsmark. Fifty of the lineaments are completely new along their full extension. Twenty-six of the previous linked lineaments have not been affected by this work and are thus keeping its previous identity and extent. Twenty previous lineaments are extended outside the Forsmark regional model area and are in some cases also modified within the Forsmark regional model area. For the latter, earlier identities are retained.

Of all linked lineaments, 24 are classified as regional (length > 10 km) and 72 are local major (1–10 km in length), respectively.

Both the method-specific/co-ordinated lineaments and linked lineaments generated in this work are delivered as along with the basic and processed data used.

Sammanfattning

Den regionala deformationszonsmodellen för Forsmark ska utvidgas till att omfatta avrinningsområdet med planerad tillämpning inom SDM-SAR.

En tolkning av lineament, vilka utgör basen för ytterligare modellering av deformationszoner, har utförts inom ett avgränsat arbetsområde som omfattar avrinningsområdet, "Site Descriptive Model – Safety Assessment Report" area, SDM-SAR.

Deformationszonernas minsta längd i kommande arbeten är fastställd till 5 km. Däremot kommer lineamentstolkningen att följa principerna vid tidigare liknande arbeten och således ha en minsta längd på ungefär 3 km.

Utgående ifrån visualisering av olika magnetiska, VLF- och höjddata har lineament identifierats, ritats in som vektorer och beskrivits.

Tolkning av lineamenten har utförts i enlighet med den metod och den strategi som använts i tidigare arbeten med Forsmark platsmodell. Kort utgår dessa från att magnetiska data betraktas som den säkraste källan för att identifiera deformationszoner genom huvudsakligen lågmagnetiska lineament. I detta arbete innefattar metodiken därmed att identifiera, rumsligt beskriva och dokumentera förekomsten av magnetiska lineament i första hand. Befintliga topografiska data och flyggeofysiska VLF-data har använts som stöd för att identifiera de magnetiska lineamenten samt för att bättre följa de magnetiska lineamenten.

De magnetiska lineamenten klassificeras i låg, måttlig och hög osäkerhet huvudsakligen baserat på hur tydligt de framträder, men även utifrån en bedömning av den specifika geologiska situationen och den möjliga orsaken till lineamentet. I detta arbete kan två huvudgrupper av magnetiska lineament utskiljas:

- Magnetiska diskordanta minima, det vill säga avvikande från geologiska och geofysiska trender.
- Magnetiska konkordanta minima konnektioner, det vill säga i huvudsak överensstämmande med geologiska och geofysiska trender.

Lineamenten beskrivs med attributdata i en tabell med samma innehåll som i tidigare arbeten. Av särskilt intresse är attribut som karaktär, osäkerhet, längd och medelriktning samt utifrån vilken metod ett lineament har identifierats. Ett viktattribut beaktar både osäkerhetsgraden och antalet metoder i vilket ett lineament har identifierats. Viktattributet ger en indikation på graden av konfidens för ett lineament.

De magnetiska lineamentsegment som först identifierades (metodspecifika/ koordinerade lineament) kopplas därefter samman till länkade lineament. I detta skede av arbetet inkluderades även länkade lineament från tidigare arbeten, modellversion 2.2.

I detta arbete har totalt 96 länkade lineament genererats, att jämföra med 44 länkade lineament i tidigare regionala modellversion 2.2, SDM-Forsmark. Femtio av lineamenten är helt nya längs hela sträckningen. Tjugosex av de tidigare länkade lineamenten har inte påverkats av detta arbete och behåller således dess tidigare identitet och sträckning. Tjugo av de tidigare tolkade lineamenten har utvidgats utanför det tidigare regionala modellområdet och har i vissa fall även modifierats inom det tidigare regionala modellområdet. För dessa behålls tidigare identitet.

Av alla länkade lineament är 24 klassificerade som ”regionala” (längd > 10 km) och övriga 72 klassificeras som ”lokala större” (> 1 km samt < 10 km).

Leveransen omfattar metodspecifika/koordinerade lineament, länkade lineament samt de grundläggande och bearbetade flyggeofysiska data som använts för detta arbete.

Contents

1 Introduction

The regional deformation zone model for Forsmark will be expanded to include the catchment area for planned applications within the SDM-SAR (*Site Descriptive Model-Safety Assessment Report*) area. The area is slightly larger than the defined Forsmark Baseline model area, but in order to avoid later retakes, it has been decided to use the catchment area for the integrated SDM-SAR as the area of delimitation.

An interpretation of lineaments, forming the base for further deformation zone modelling, will be carried out within a delimited work area including the catchment area, SDM-SAR, see Figure 1-1. The lineament interpretation intends to identify lineaments as a basis for completing the existing deformation zone model for Forsmark with zones exceeding 5 km or more in ground surface trace length, also outside the regional model area, SDM Forsmark.

The work has been carried out by GeoVista AB in accordance with instructions and guidelines as directed by SKB in the activity plan AP SFK 19-039, the method descriptions MD 211.003, MD 212.004 and MD 120.001, Table 1-1. Both the activity plan and the method descriptions form SKB's internal controlling documents.

Identification of topographic and airborne geophysical lineaments has been carried out in the site investigations at Forsmark (Isaksson 2003, Isaksson et al. 2004, 2006a, b, 2007, Korhonen et al. 2004, Isaksson and Keisu 2005, Johansson 2005). The lineaments have mainly been identified as magnetic lows. In several cases, linked lineaments have been verified as representing deformation zones in the bedrock, whereas others have alternative geological explanations (Johansson and Isaksson 2006).

Linear features, or lineaments, can provide important information on the existence and extensions of deformation zones in the bedrock. The magnetic susceptibility of rocks is often low in fractured, altered or porous bedrock due to destruction of ferromagnetic minerals. Hence, the work forms a basis for the geological bedrock mapping and the site descriptive models in the Forsmark area (SKB 2004, 2005, Stephens et al. 2007, Stephens and Simeonov 2015).

Table 1-1 lists the activity plan and method descriptions used as governing documents for the work.

Table 1-1. Controlling documents for carrying out the activity.

Activity plan	Number	Version
Lineamentstolkning ut till avrinningsområde Forsmark	AP SFK-19-039	1.0
Method descriptions	**Number**	**Version**
Metodbeskrivning för lineamentstolkning baserad på topografiska data	SKB MD 120.001	1.0
Metodbeskrivning för tolkning av flyggeofysiska data	SKB MD 211.003	1.0
Metodbeskrivning för markbaserad magnetometri	SKB MD 212.004	1.0

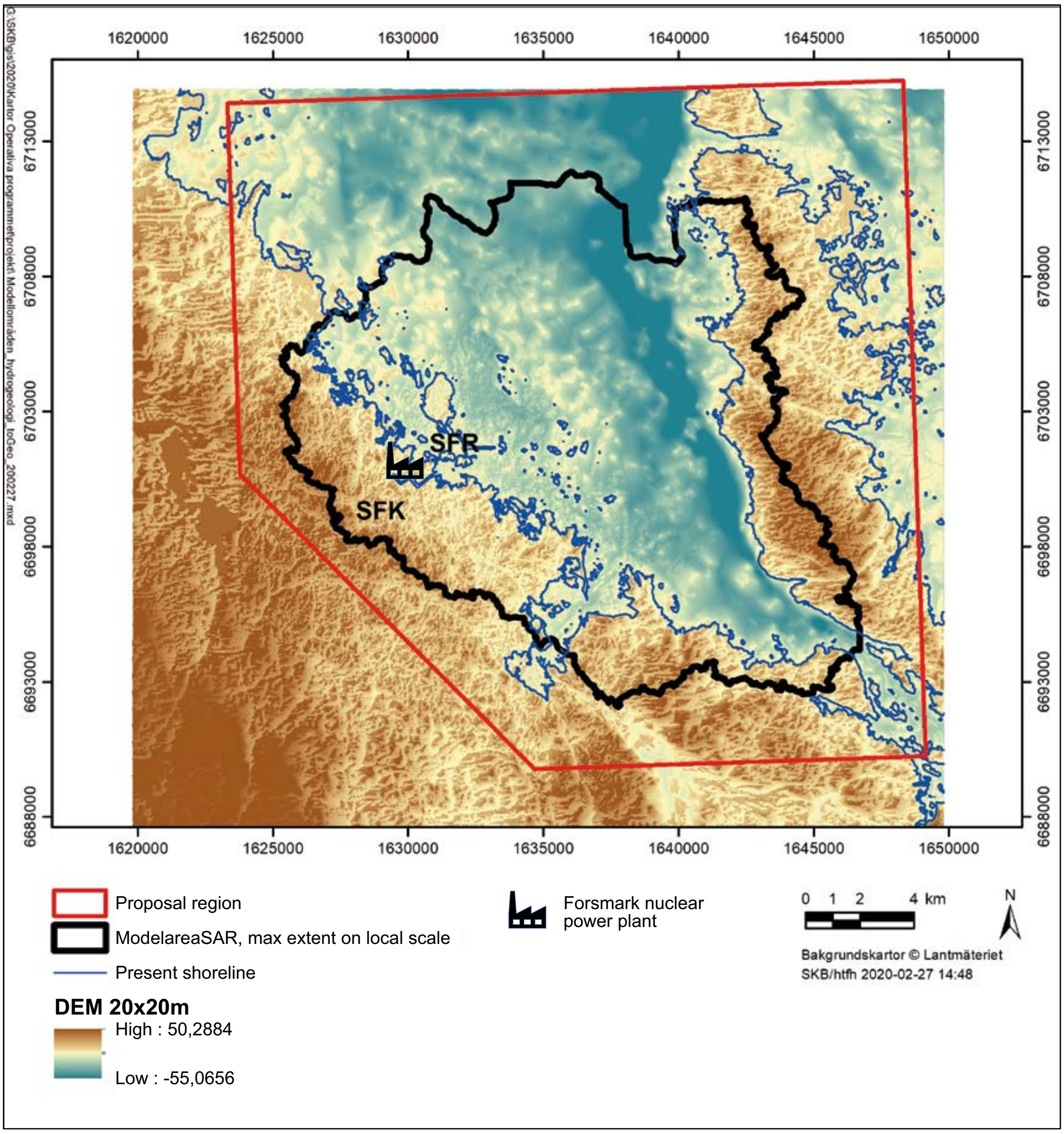

Figure 1-1. *Topography map showing the Forsmark SDM-SAR catchment area (black line) and the work area for lineament interpretation (red line).*

2 Methodology

2.1 Available data

The work area is covered by low-altitude airborne geophysical surveys, predominantly generated by the Geological Survey of Sweden (SGU) in connection with their standard mapping activities. However, surveys have also been carried out by Geological Survey of Norway (NGU) on behalf of SKB and Boliden for exploration purposes. Table 2-1 presents the various surveys in the area and respective survey parameters. Figure 2-1 shows a compilation of the magnetic field in the region.

Table 2-1. Survey parameters for airborne geophysical surveys in the study area. All surveys have been carried out in the Swedish grid RT90, 2.5 gon W, 0: −15.

Survey area	Forsmark (power plant)	13I SV, NV Österlövsta	12I Östhammar	13I Österlövsta	Forsmark PLU
Contractor	SGU	Boliden	SGU	SGU	NGU
Flight year	1977	1979	1982	1998	2002
Survey direction	35°	N-S, 0°	E-W, 90°	E-W, 90°	S-N, 90°
Line spacing	200 m	Ca 150 m	200 m	200 m	50 m
Grid cell size	40 m	40 m	40 m	40 m	10 m
Ground clearance	30 m	30 m	30 m	60 m	45 m
Reference	(Bergman et al. 1999)	(Bergman et al. 1999)	(Bergman et al. 1999)	(Bergman et al. 1999)	(Stephens et al. 2007)

Specifically, for this lineament interpretation work, the following datasets have been used, with the areal coverage illustrated in Figure 2-2:

(1) A specific regional magnetic grid mosaic, originating from previous work with "Förstudie Tierp" (pre-investigation for Tierp municipality), Figure 2-3. For this grid (40 × 40 m grid cells), an aggregation of the various airborne measurements from 1977–1998 (Table 2-1) and the latest processing had been made. Above all, a so-called upward continuation was carried out, i.e. a transformation of measurement data from 30 m ground clearance to a common measurement plane of 60 m above ground (Bergman et al. 1999). For this dataset, current enhancements techniques have been applied, see Section 2.2.

(2) From the SGU 1998 survey (Table 2-1) magnetic data was ordered 2019 from SGU (red square in Figure 2-1) in order to get the most modern data with most recent corrections, e.g. for the Fenno-Skan, HVDC cable. For this dataset, current enhancements techniques have been applied, see Section 2.2.

(3) The previous, helicopter-borne, magnetic grid data (10 × 10 m) from the Forsmark survey 2002 (Stephens et al. 2007) (Table 2-1), was recovered and in this work, processed with current enhancements techniques, see Section 2.2.

(4) The SGU 1982 regional survey (Table 2-1) the VLF total field, 40 × 200 m grid, for map-sheets 12I Östhammar NW and NE (Table 2-1) was recovered from "Förstudie Östhammar" (Bergman et al. 1996[1]). This VLF data is based on one transmitter only and thus has a limited use due to the directional dependence.

(5) From the SGU 1998 regional survey (Table 2-1), the VLF total field and resistivity data were ordered for a selected area (Figure 2-1). The VLF resistivity data is based on two transmitters and thus directional dependence is minimized. The VLF total field data recorded from each of the individual transmitters has a limited use due to the directional dependence.

[1] **Bergman S, Isaksson H, Johansson R (ed), Lindén A, Persson C, Stephens M, 1996.** Förstudie Östhammar. Jordarter, bergarter och deformationszoner. SKB PR D-96-016, Svensk Kärnbränslehantering AB. (in Swedish.) (Internal document.)

(6) Elevation data was provided by SKB as a 20 × 20 m grid merged from bathymetric Sea data and a Land survey 1 × 1 m elevation grid. Swedish grid Sweref 99 18 00.

(7) Elevation data 50 × 50 m grid from The Swedish National Land Survey, Lantmäteriet, open data (GSD-Höjddata, grid 50+).

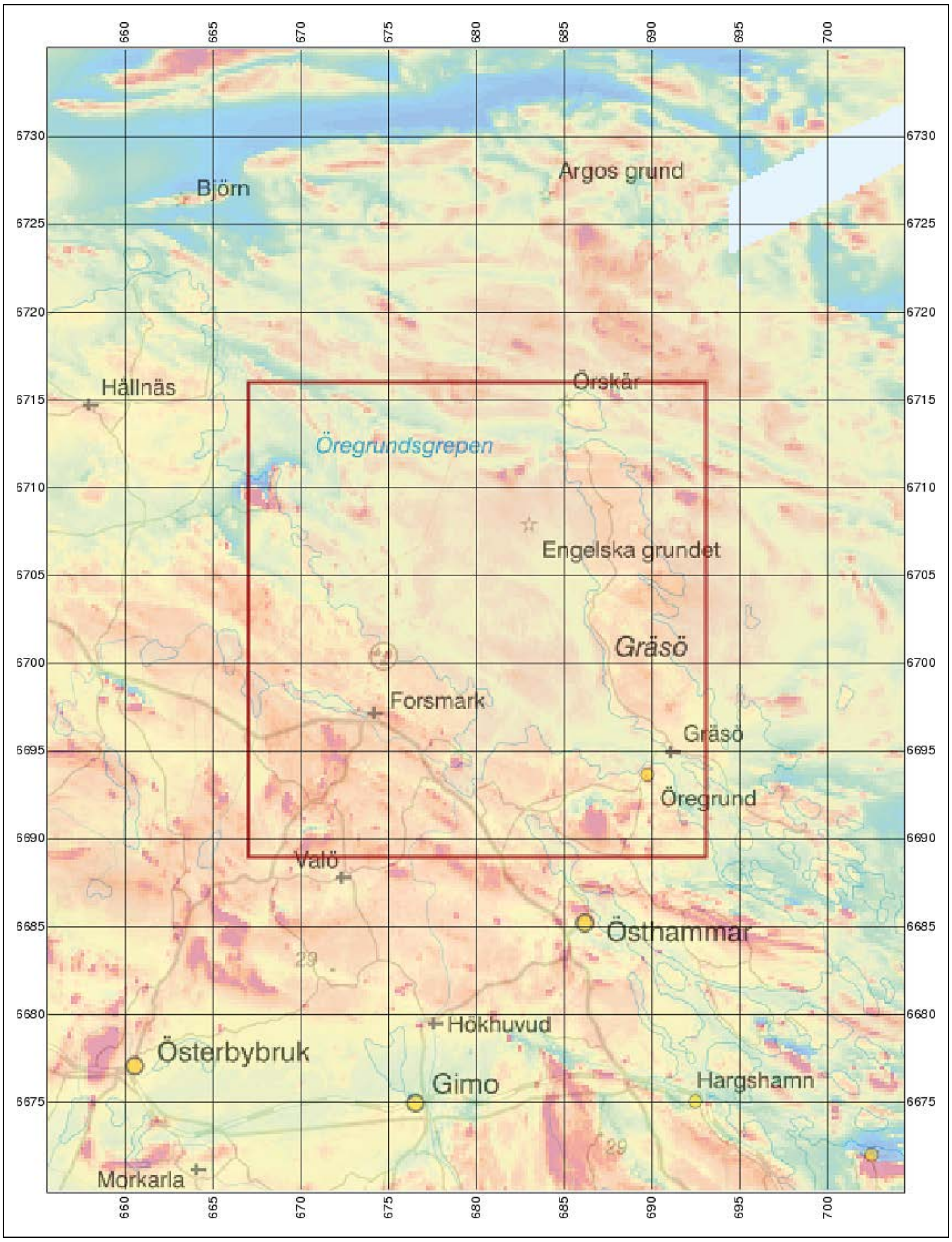

__Figure 2-1.__ Forsmark area, regional magnetic field compiled by SGU, November 2019. Red square shows the area for which data has been acquired and further processed in this work. Swedish grid Sweref 99 TM. To get co-ordinates in meters multiply by 1 000.

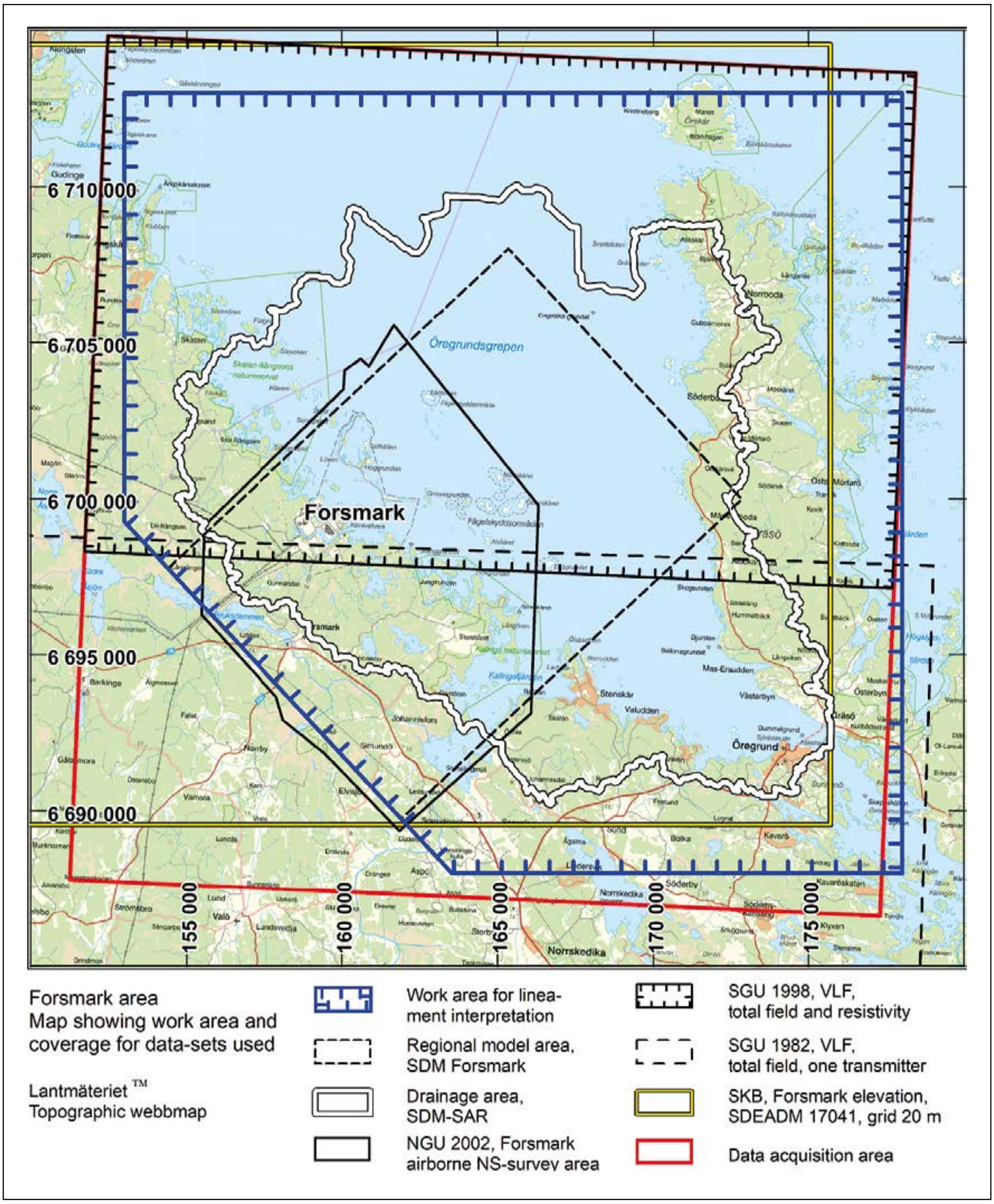

Figure 2-2. *Available data coverages for the lineament interpretation work area.*

2.2 Data processing

The magnetic data, (1) and (3) above, has previously been interpolated to 40 × 40 m and 10 × 10 m grids, respectively, using linear Kriging in the Surfer software (™ Golden software) (Stephens et al. 2007, 2008b). The magnetic data ordered in this activity, see (2) in Section 2.1, has been treated in the same manner.

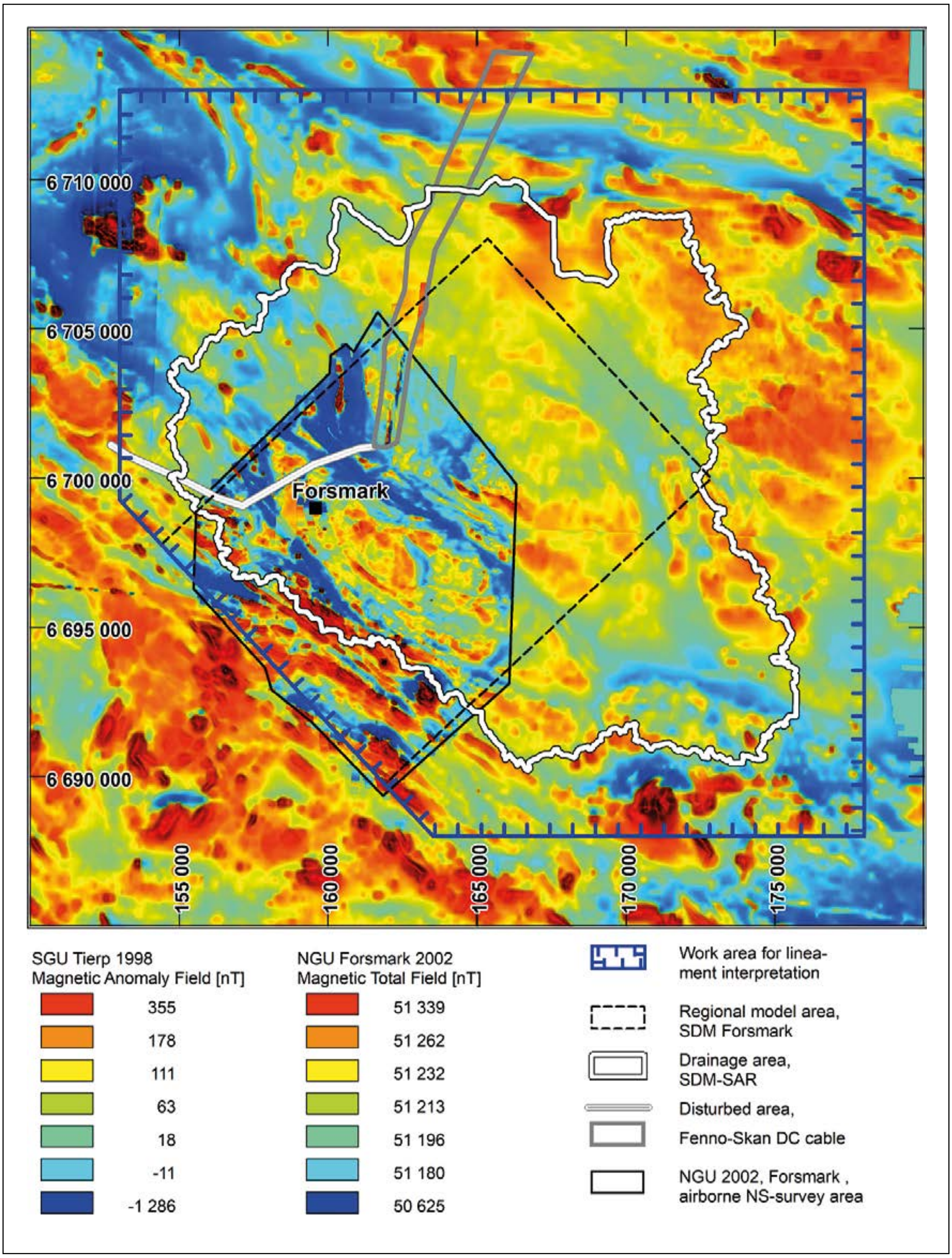

Figure 2-3. Airborne magnetic anomaly field from "Förstudie Tierp" and an inset map with magnetic total field from NGU Forsmark 2002.

For data enhancement and to facilitate identification and mapping of geological structures, bedrock magnetic patterns and specifically lineaments for this activity, a package of transformations and filters have been applied to the interpolated magnetic grids, including reduction to the pole (RTP), upward continuations (Uc), horizontal and vertical derivatives (dX, dY, dH, Vd1, Vd2), analytical signal (AS) and tilt derivatives (TDR, TDRdH). The magnetic field and a selection of processed data layers are presented in Figure 2-4 and 2-5.

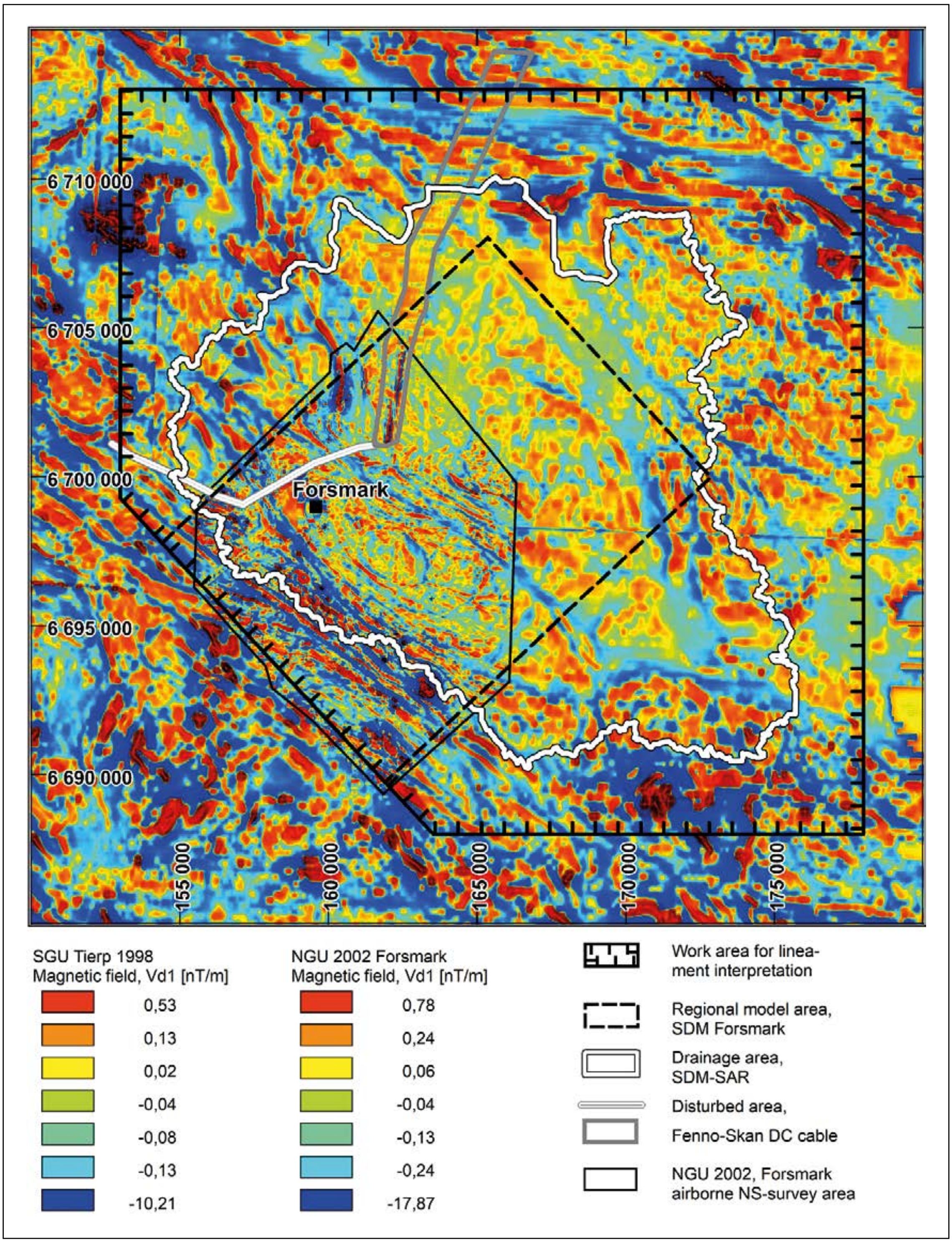

Figure 2-4. *Vertical derivative of airborne magnetic anomaly field from "Förstudie Tierp" and the inset map with vertical derivative of magnetic total field from NGU Forsmark 2002.*

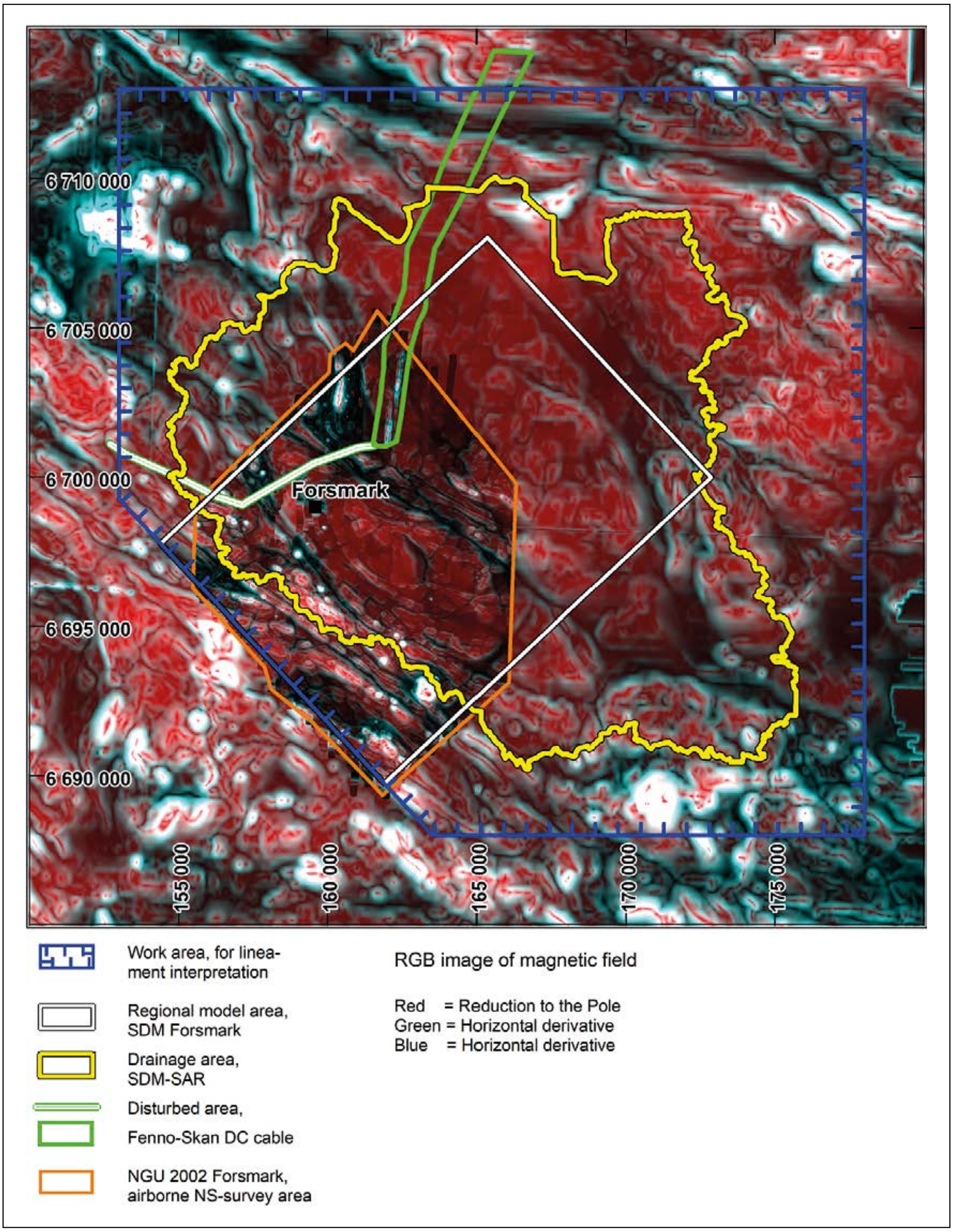

Figure 2-5. *Airborne magnetic anomaly field from "Förstudie Tierp" and an inset map with magnetic total field from NGU Forsmark 2002. Colour composite of reduction to the pole (red) and horizontal derivative (green, blue).*

For the 1982 VLF data, see (4) in Section 2.1, the total field is presented as a 40 × 200 m grid (natural neighbour interpolation, Surfer software, ™ Golden software), Figure 2-6.

For the 1998 VLF data, see (5) in Section 2.1, the resistivity is interpolated to a 40 × 40 m grid using minimum curvature in the Discover software (™ Datamine), Figure 2-7. The total field components for each transmitter is presented as a 40 × 200 m grid (natural neighbour interpolation), Figure 2-6.

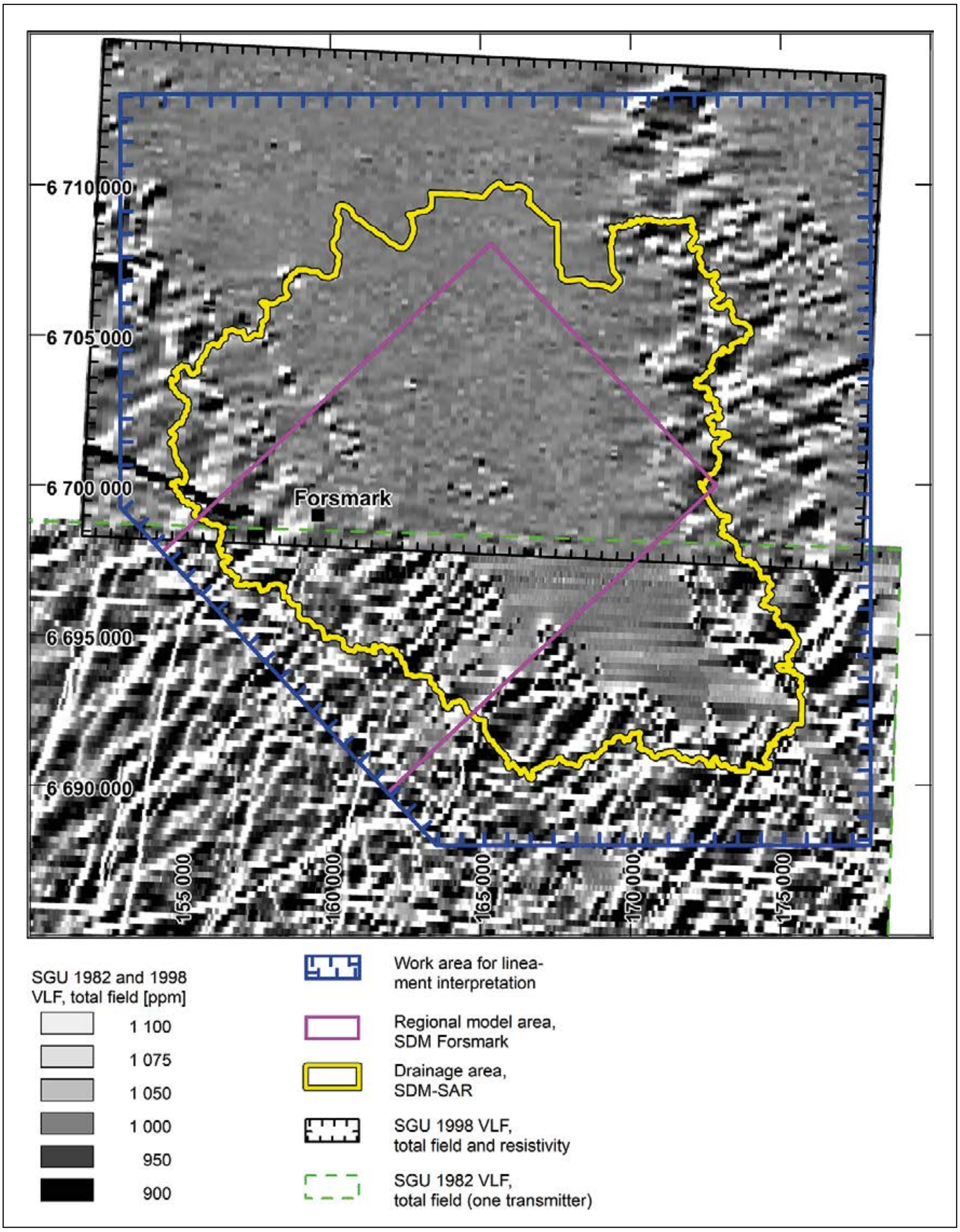

Figure 2-6. *Airborne VLF, total field, SGU 1982 (southern part) and 1998 (northern part), transmitter GBR.*

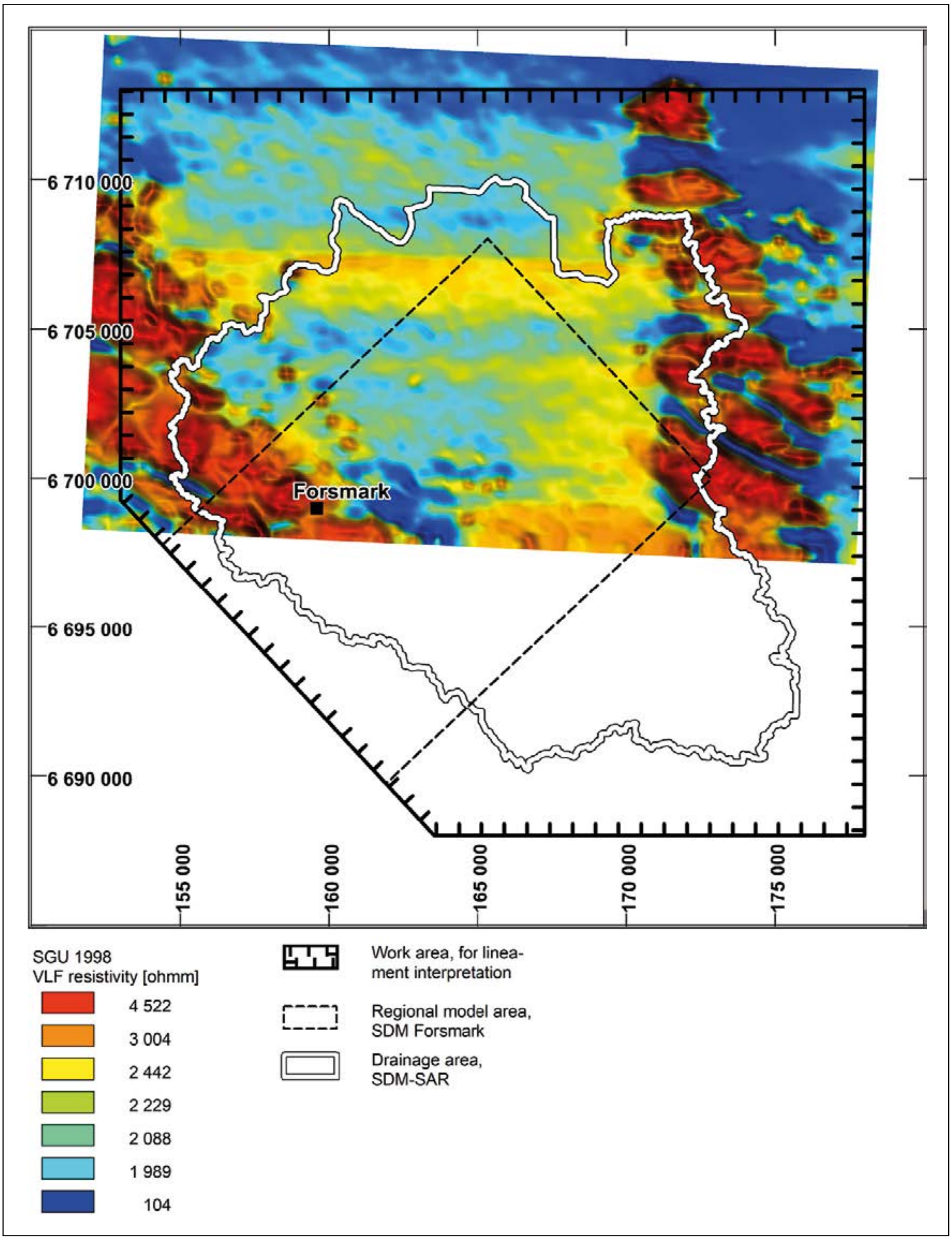

Figure 2-7. *Airborne VLF, resistivity, SGU 1998.*

For the elevation data, see (6) in Section 2.1, (Figure 2-8) the horizontal (slope) gradient has been determined using Discover software (™ Datamine). A vertical derivative has also been applied as a high-pass filter to enhance shorter wavelength variations in the elevation data, using Profile Analyst (™ Datamine). For the open elevation data, see (7) in Section 2.1, the elevation is presented as a vertically illuminated 50 × 50 m grid (Figure 2-8).

All grids are created in its original Swedish grid system and displayed in the Swedish grid Sweref 99 18 00 during the interpretation work carried out.

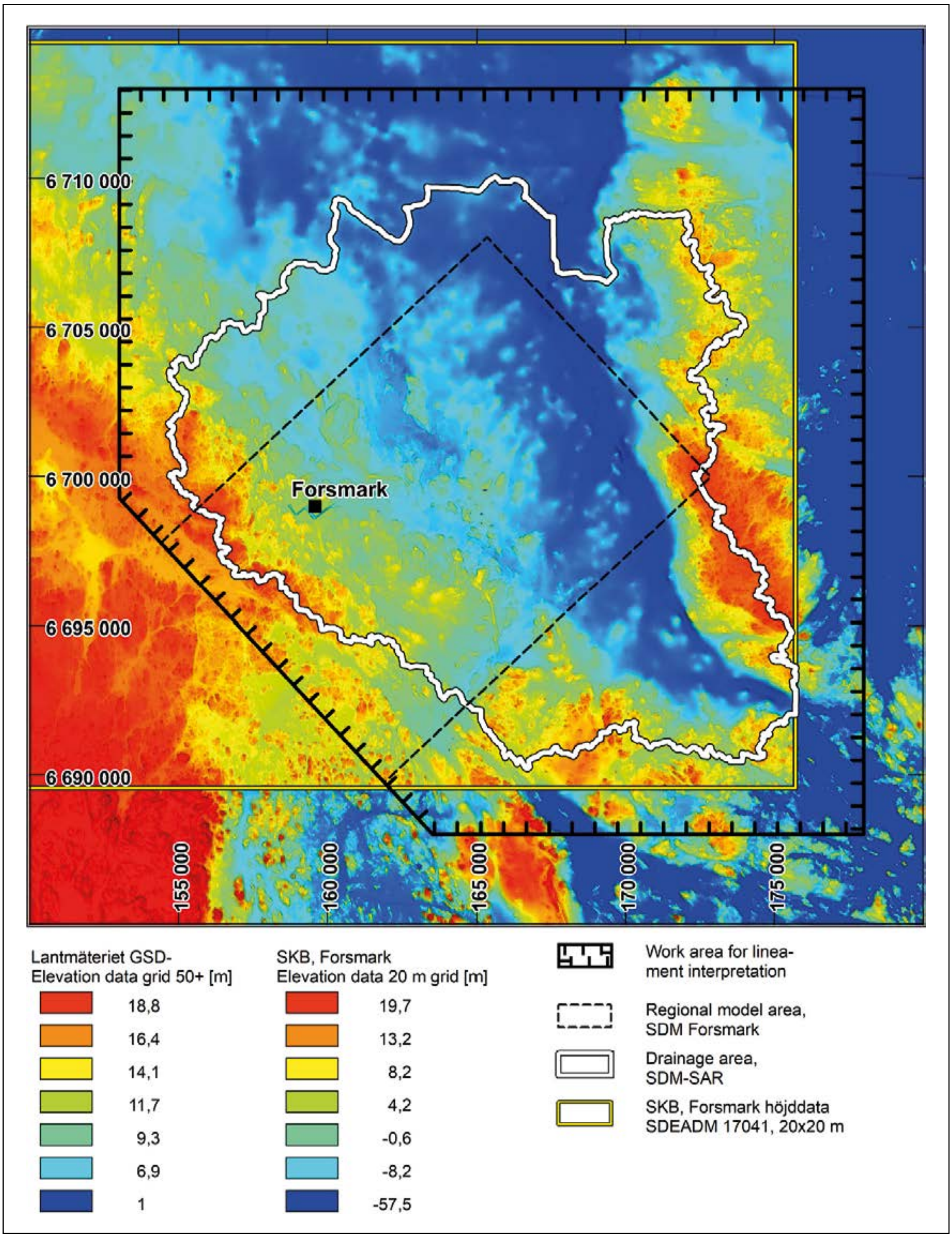

Figure 2-8. *Digital elevation data, GSD-Höjddata, grid 50+, Lantmäteriet covering the whole work area and a 20 m grid provided by SKB. The latter is a mosaic of detailed land-based elevation data and bathymetric data from the Sea.*

2.3 Lineament interpretation

2.3.1 General

Lineaments are determined by identification and outlining of vectors using visualization of the various magnetic, VLF and elevation datasets in a GIS system, in this case MapInfo Pro and Discover software (™ Pitney Bowes and ™ Datamine, respectively).

The methodology for interpretation and documentation of lineaments has previously been well described by Isaksson and Keisu (2005). From experiences during modelling version 2.1, lineaments identified in topographic data showed major uncertainties, with the ground surface inconclusive in expressing the bedrock morphology. Electromagnetic methods such as active and passive (VLF) EM exhibited similar uncertainties, due to large topographic dependence and the proximity to coastal marine saltwater. Both topography and electromagnetic data also have poor spatial resolution and reproduction in the area covered by oceans and lakes, while airborne magnetic data provide a more uniform basis for assessment. Thus, it was decided to rely future work mainly on magnetic data, with only limited support from EM, VLF and topography, as a basis for lineament interpretation (Stephens et al. 2007).

Interpretation of lineaments shall be in accordance with the methodology and strategy described and applied from the following reports: Isaksson and Keisu (2005), Isaksson et al. (2007) and Stephens et al. (2007, 2008a). Stephens et al. (2007, Section 3.9) "Low-magnetic lineaments – identification and geological interpretation", presents the reason for, as well as, the strategy and methodology used in the latest modelling of deformation zones in Forsmark. In short, it presumes that magnetic data is considered more reliable for identifying steeply dipping deformation zones as mainly low magnetic lineaments. The method is most efficient for sub-cropping deformation zones and has a weakness in flat-lying or horizontal zones that in general are harder to identify.

Thus, this work is based on the methodology mentioned above to identify, describe and document the spatial occurrence of magnetic lineaments in the first place. Existing topographic data and airborne geophysical VLF data are used as a support for identifying magnetic lineaments and for better tracing location and propagation of a magnetic lineament. In exceptional cases, solely topographic or VLF lineaments may be included if they are suspected to correspond to a flat-lying or gently dipping deformation zone. For lineaments with nearby but different sub-cropping in magnetometry and topography or EM, the position of the magnetic lineament is stated while the relationship is described in the comment attribute. This procedure can be described as simultaneously combining the operation to determine method specific lineaments (Stage 1) and coordinating method specific lineaments into co-ordinated lineaments (Stage 2) (Isaksson and Keisu 2005).

The magnetic lineaments identified are graded in low, medium and high uncertainty, mainly with respect to the clarity in which they appear but also, in some cases, involving a judgement regarding the specific geological situation and the possible cause of the lineament. Typically, lineaments appear as linear magnetic minima, edges and dislocations in the magnetic field.

In Andersson (2003), the various stages of assessment of uncertainty and confidence in interpretations, descriptive modelling and integrated evaluations are discussed. In this work, the interpretation of lineament segments is initially carried out based on each individual geophysical and topographical data and, at this stage, each lineament is assigned an uncertainty graded from 1 = low to 3 = high.

By interpreting a lineament in additional data, a weight attribute is supplemented. A weight attribute considers both the degree of uncertainty and the number of methods in which a lineament has been identified. The weight attribute assessment yields an indication of the confidence (Andersson 2003) of a co-ordinated or linked lineament, graded from 1 = low to 5 = high. The weight attribute is further described and discussed in Isaksson and Keisu (2005).

The structural geology in the Forsmark area is characterized by variably intense ductile deformation of both supracrustal and intrusive rocks. Hence, also the intrusive rocks commonly show a strongly banded component in the magnetic pattern. It is difficult to decide whether lineaments appearing as minima parallel to the general bedrock foliation are related to fracture zones or to variability in the distribution of rock types with low magnetization and, in that sense, could be characterized as low-magnetic connections. In this work, these linear features are identified as lineaments with a separate character named "minima connections". As in previous work, three major groups of magnetic lineaments are distinguished by their nature:

- Magnetic minima, discordant to geological and geophysical trends.
- Magnetic minima, concordant to geological and geophysical trends.
- Magnetic lineaments with a dyke-like character.

The lineament is described with attribute data in a table with the same content that has been used in previous work and which is described, inter alia, in Table 4-2 of Isaksson et al. (2007). Notable are attributes such as character, uncertainty, length and mean direction and method of identification: magnetic, topographical and/or conductive (EM). The attribute table is presented in Appendix 1.

The magnetic lineament segments initially identified (method specific/co-ordinated lineaments), subsequently were linked together into a linked lineament. At this stage, linked lineaments from previous work, model version 2.2, were also included.

Identification or naming of lineaments will be based on past routines where MFM followed by a serial number is used for the magnetic lineaments. Lineament that connects/links to previously interpreted lineament, model version 2.2, is given the previous lineament identity. New lineaments, not previously identified, start with identity MFM3500.

Both the method-specific/co-ordinated lineaments and linked lineaments generated in this work are delivered.

2.3.2 Specific conditions for SDM-SAR

Lineament interpretation shall be carried out to enable modelling of deformation zones with a minimum ground surface trace length of 5 km, up to and beyond the boundary of the SDM-SAR catchment area. This also includes an extension of all previously modelled zones that are truncated along the boundary for the Forsmark regional model area. This regardless of whether the zone ground surface trace length exceed 5 km or not (cf. Figure 2-9). Thus, there should be no artificial truncation of a lineament between the Forsmark regional model box and the surrounding catchment area, see also Figure 2-2.

However, the lineament interpretation will be carried out in accordance with previous similar lineament interpretations and thus a lineament will have a minimum ground surface trace length of 3 km. Lineaments shorter than 3 km may, in exceptional cases, be included in the case where they constitute a termination of a longer lineament or if they, for a short distance, constitute an alternate or parallel route to the main lineament.

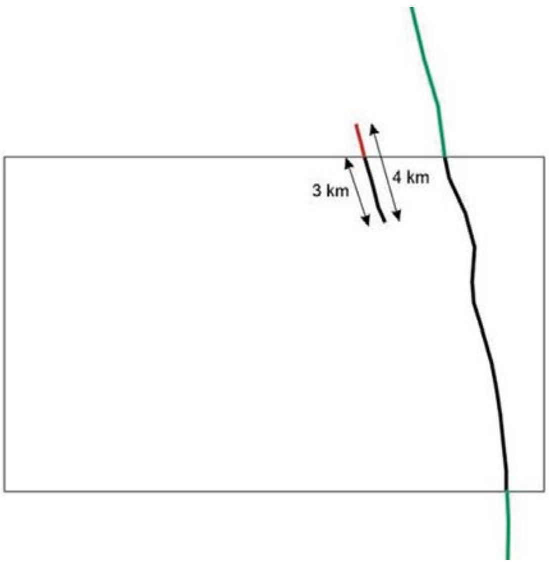

Figure 2-9. Sketch enlightening treatment of lineaments at the boundary of the Forsmark regional model area.

2.3.3 Uncertainties in lineament interpretation

The lineaments are graded in low, medium and high uncertainty, basically with respect to the clarity in which they appear. However, also some other specific uncertainties can be pointed out regarding magnetic lineaments and their character.

Differences in magnetic properties in the bedrock give different premises for identifying lineaments. A homogenous rock unit with high magnetic susceptibility makes it easier, while an inhomogeneous or low magnetic rock unit will make it harder.

Differences in overburden thickness, or water depth, also give different premises for lineament identification. Large areas with a thin overburden give a better spatial and dynamic resolution of the magnetic pattern and hence, lineaments are more easily identified.

Topographical subsurface features like linear depressions in the bedrock surface can give rise to a locally deeper overburden and hence, also cause a linear magnetic low which not necessarily correspond to a change in bedrock susceptibility due to fracturing.

Horizontal to sub-horizontal structures are more difficult to identify in the magnetic field and when they occur, they may appear as curved features, partly following the topography.

The geophysical survey direction will make it easier to identify structures perpendicular to the main sampling direction.

The Fenno-Skan HVDC cable affects the magnetic and EM surveys. The areas affected by the cable are outlined as a disturbance area.

When linking two coordinated lineaments, there is in some cases more than one way to do it. How the linking is made will also have a major influence on the final length of the linked lineament.

In some cases, a long lineament with in general low uncertainty can have a short, highly uncertain intermittent segment in between the longer segments. These conditions have a low impact in the applied methodology. The weighted average according to length of each segment will give the possible discontinuity a very low significance.

In this work, lineaments are not terminated at the interpretation boundary. However, some of the regional structures propagate over a significant distance or even outside of the data coverage, and thus, such terminations can be hard to establish. Consequently, for such lineaments, the lengths should be considered as a minimum length.

The airborne magnetic data used in previous regional, large-scale lineament interpretations matches a lineament representation at a scale of 1:50 000 – 1:100 000 in the open sea area (Öregrundsgrepen), and a scale of 1:20 000 – 1:50 000 in the coastal area as well as on the mainland (Isaksson et al. 2004, Korhonen et al. 2004, Isaksson and Keisu 2005). Previous detailed work based on detailed ground magnetic surveys provide a scale of around 1:5 000 (Isaksson et al. 2006a, b, 2007). Most of the work carried out in this activity is of regional character, thus, providing a scale around 1:50 000.

Precision in previous work was in general around ± 20 m (10–50 m) and in this work mostly estimated to around ± 50 m (20–100 m).

Work based on more detailed data will commonly provide a finer resolution of structures that will fade away in coarser scales and data. Longer lineaments at a regional scale will, at a detailed scale, be divided into shorter and often more non-coherent segments.

3 Results

The interpretations are stored in GIS-format and each lineament has an attribute table attached, Appendix 1, identical to the one previously used in Isaksson et al. (2007). The table is the same for method specific/coordinated and linked lineaments, which means that the significance of the individual attributes is somewhat different for each representation. Origin, method, character and uncertainty are important attributes for the lineaments. The mean length and direction of each lineament segment is calculated and provide a basis for classification into regional or local major lineaments (Andersson 2003). The weight attribute is a classification of uncertainty and the number of indicating properties (Isaksson and Keisu 2004). Variable line thickness can be used to display the weight of a lineament, Figure 3-1.

Identity is only preliminary for method specific lineaments while, for linked lineaments, the identity attribute is completed.

Beside scrutinizing the lineaments as possible deformation zones, the comprehensive attributes table also provide a basis for further statistical analysis (e.g. Isaksson et al. 2007). However, such an analysis has not carried out in this work.

3.1 Method specific lineaments

The new magnetic, method specific, lineament dataset constitute of in total 167 lineament segments. Of these, 113 are completely new (Id_t = "new") and 54 new segments have been extended from lineaments already present in the regional model area (Id_t = "previous identity + direction and segment number). Seventy-four lineament segments are classified as being minima connections (mostly). The new, method specific, magnetic lineaments identified in this work are presented in Figure 3-1.

Two topographic lineament segments with no obvious coinciding magnetic appearance have been identified.

No magnetic lineaments with dyke-like character have been identified in this work.

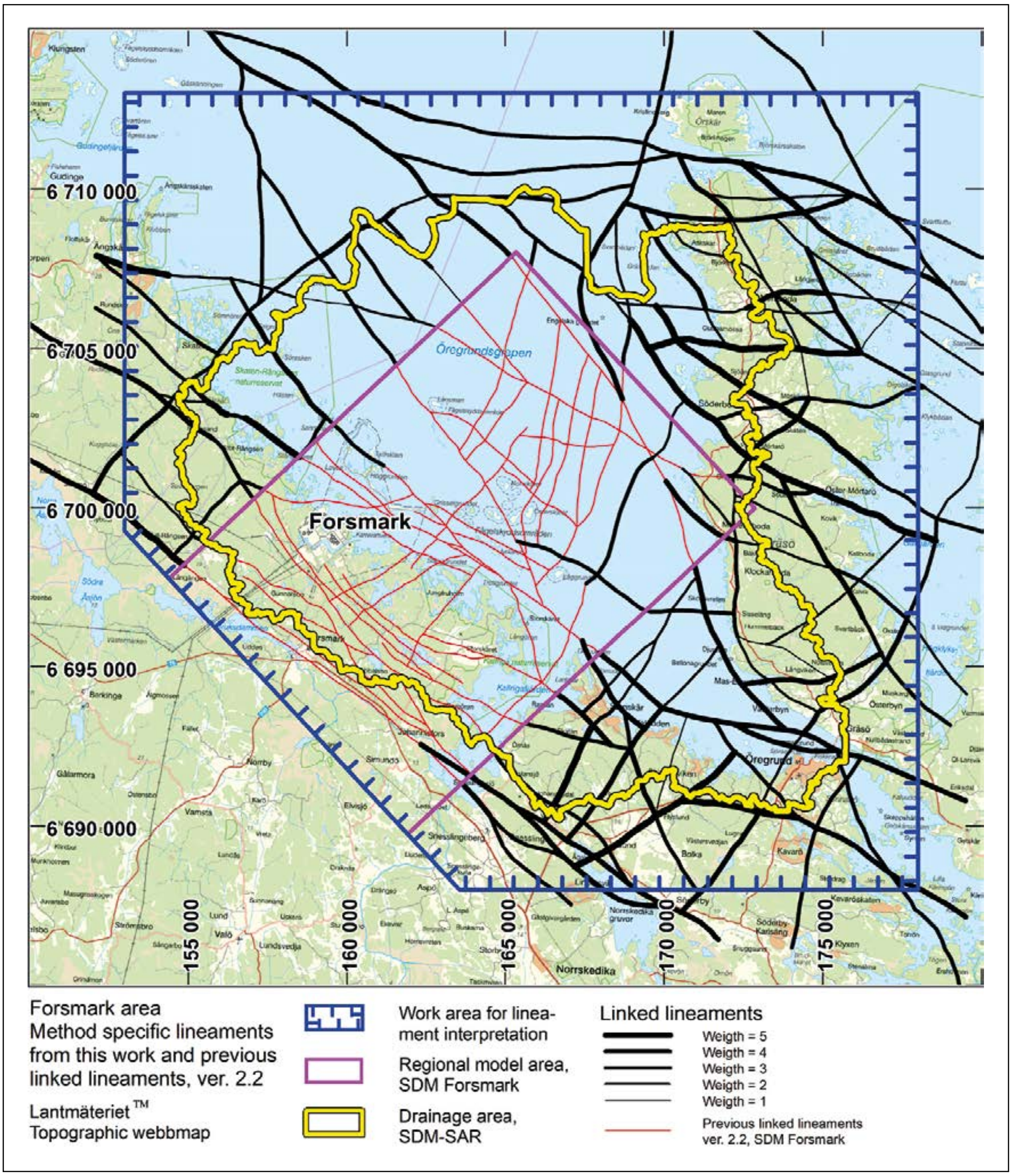

***Figure 3-1.** Method specific lineaments generated in this work.*

3.2 Linked lineaments

From the linking process, including previously linked lineaments from the Forsmark regional model area, in total 96 linked lineaments have been identified, to compare with 44 lineaments in previous regional model version 2.2 (Stephens et al. 2008a). The new linked lineaments from this work are presented in Figure 3-2.

Fifty of the lineaments are completely new along their full extension. They are given the identity MFM3500–MFM3549.

Twenty-six of the previous linked lineaments have not been affected by this work and are thus keeping its previous identity and extent.

Twenty previous lineaments are extended outside the Forsmark regional model area and are in some cases also modified within the Forsmark regional model area.

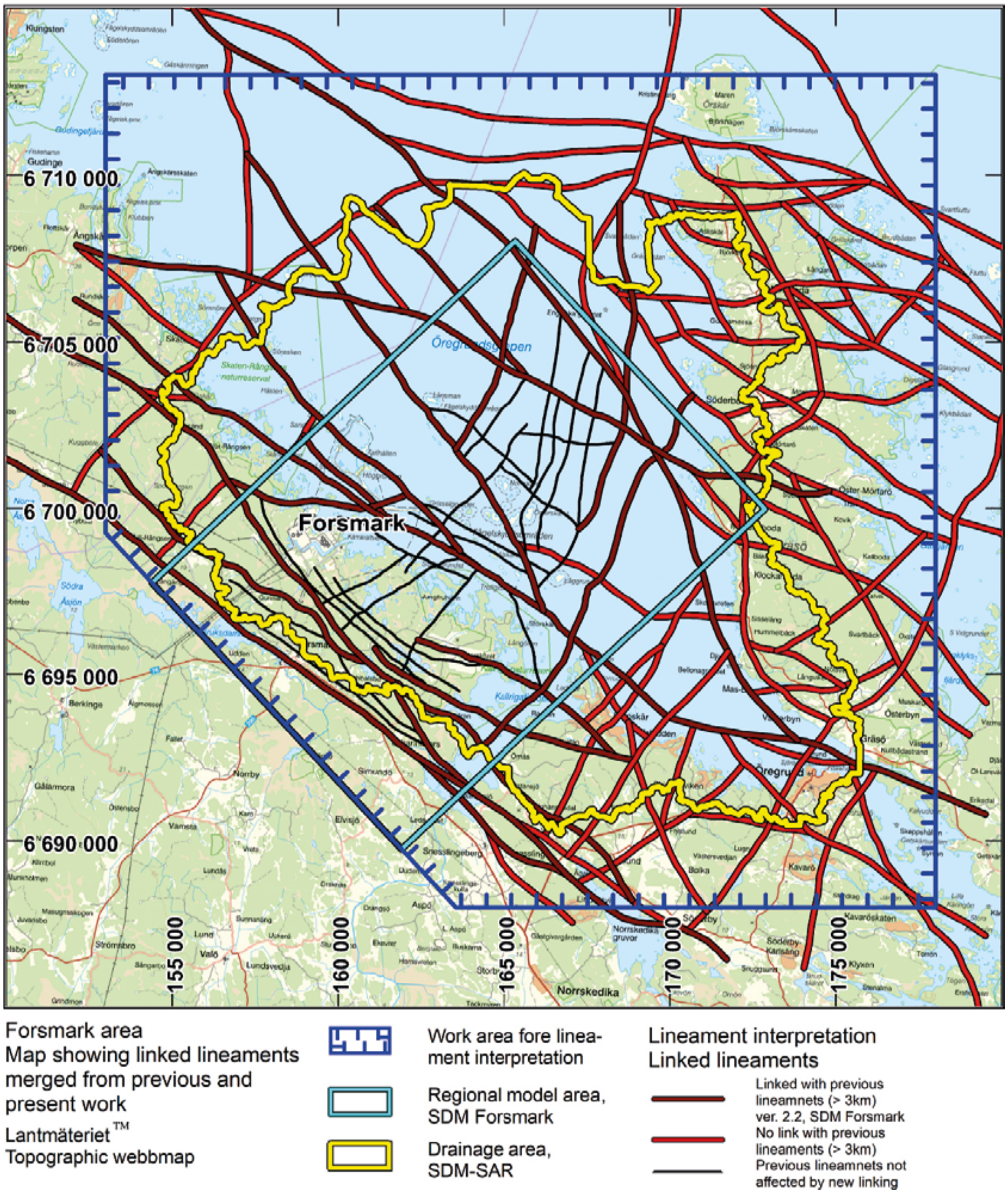

***Figure 3-2.** Linked lineaments generated in this work.*

Two previous lineaments, MFM0805 and MFM0828, are extended, both within and further outside the Forsmark regional model area. One previous lineament, MFM0014A, has an added splay within, and a new main route outside, the regional model area. Furthermore, one previous lineament, MFM0016, has been modified within the Forsmark regional model area, along 600 m of its south-east end. The lineament now bends slightly towards south before continuing into the SDM-SAR model area.

Brand new lineaments running in the Forsmark regional model area are: MFM3529, 3531, 3532, 3534, 3535, 3538 and 3548.

In the process of determining deformation zones, it is recommended to study details of the new lineaments in the Forsmark regional model area.

It was recognized during the work that, for some of the previous linked lineaments for the Forsmark regional model area (SDEADM_GV_FM_GEO_6043), the weight attribute was below 1, which is invalid. In the new linked lineament version, the weight attribute is corrected for 17 lineaments: MFM0014, 0016, 0017G, 0036, 0060G0, 0062G0, 0123G0, 0137, 0137BG, 0808A0, 0808B0, 0808CG, 0823, 0835BG, 0842, 1133, 1134.

Of all linked lineaments, 24 are classified as regional (length > 10 km) and 72 are local major (1–10 km in length), respectively.

4 Data delivered

Data delivery covers lineaments generated in this work, airborne geophysical data, grids, processed grids and images. Digital elevation data used in this work is not delivered since SKB already have the data in-house. Data is delivered in its original Swedish grid system, that is, the grid system used for the survey. The following digital data are delivered in connection with this report:

Table 4-1. File description, "raw" data delivered by SGU, Nov-2011 (contents in SGU_Data_leverans_20191114.zip). And, recovered data from previous work with references.

Filename	Description
AERO_EM_FM_AVR.xyz	SGU 1998 Airborne EM ascii xyz file
AERO_MAG_FM_AVR.xyz	SGU 1998 Airborne Mag ascii xyz file
Geofysiska-flygmatningar-elektromagnetiska-falt-vlf-detaljerad-beskrivning.pdf	Descriptions of SGU 1998 EM and,
Geofysiska-flygmatningar-magnetfalt-detaljerad-beskrivning.pdf	magnetometry datasets and,
META_AERO_MAG_FM_AVR.pdf	data coverage area (see also Figure 2-2)
R12I_N.XYZ	SGU 1982, Airborne VLF ascii xyz file
R12I_S.XYZ	12I Östhammar, North and South
SKB PR D-96-016_frontpage.pdf	Reference to SKB report
Fm_NGU_ns_Magn_krns1_2003_geosoft.GRD	Helicopter-borne, magnetic data, 10 × 10 m grid from the Forsmark PLU survey, NGU 2002, NS direction only
…\doc\… *.pdf P-03-41, P-03-60, P-04-29, P-04-282, R-07-45	Various SKB reports referring to this dataset
TIEM_2000_geosoft.GRD	Regional airborne magnetic grid mosaic 40 × 40 m grid, from "Förstudie Tierp", 2000, geosoft format
…\doc\R-99-53.pdf FM_Tierp_magnet_20020517.doc	Various SKB reports and documents referring to this dataset

Table 4-2. File description, magnetic grids and processed files in arc ascii grid and ESRI shape formats. With prefixes:

(1) **TIE = Förstudie Tierp, regional magnetic grid mosaic, (1) in Section 2.1.**

(2) **FMBE = SGU, 13I Österlövsta, survey 1998, (2) in Section 2.1.**

(3) **Fm_NGU_ns = Forsmark, NGU survey 2002, NS direction, (3) in Section 2.1.**

Filename	Description	Unit
(3)_MTF	Magnetic total field, grid	nanoTesla [nT]
(1, 2)_MAF	Magnetic anomaly field, grid	
(1, 2, 3)_MAF/MTF_RTP	d:o, MAF or MTF, reduced to the pole	nT
		nT
(1, 2, 3)_MAF/MTF_RTPUc10dX	RTP, upward continuation 10 m,	nT/m
(1, 2, 3)_MAF/MTF_RTPUc10dY	1st x-, y- and	nT/m
(1, 2, 3)_MAF/MTF_RTPUc10dH	horizontal derivative	nT/m
(1, 2, 3)_MAF/MTF_RTPUc10Vd1	RTP, upward continuation 10 m, 1st and 2nd	nT/m
(1, 2, 3)_MAF/MTF_RTPUc10Vd2	vertical derivative	nT/m^2
(1, 2, 3)_MAF/MTF_RTPUc10AS	Analytical signal	nT/m
(1, 2, 3)_MAF/MTF_TDR	TDR = tilt derivative	radians
(1, 2, 3)_MAF/MTF_TDRdH	TDRdH = horizontal derivative of tilt derivative	radians/m
(1, 2, 3)_MAF/MTF_TDR_zerocontours_line.shp	Contours of the tilt derivative = 0 radians (polyline)	radians

Table 4-3. File description, magnetic red-green-blue, rgb images in geotiff, .tif and .tfw formats. With prefix as above, rgb = red, green, blue.

Filename	Description
(1, 2, 3)_MAF/MTF_rgb_RTPdHdH	r = Reduction to the pole g = Total horizontal derivative b = Total horizontal derivative
(1, 2, 3)_MAF/MTF_rgb_RTPVd1dH	r = Reduction to the pole g = 1st vertical derivative b = Total horizontal derivative
(1, 2, 3)_MAF/MTF_rgb_Vd1dHdH	r = 1st vertical derivative g = Total horizontal derivative b = Total horizontal derivative
(1, 2, 3)_MAF/MTF_rgb_Vd1Vd2dH	r = 1st vertical derivative g = 2nd vertical derivative b = Total horizontal derivative
(1, 2, 3)_MAF/MTF_rgb_Vd2dHdH	r = 2nd vertical derivative g = Total horizontal derivative b = Total horizontal derivative
(1, 2, 3)_MAF/MTF_rgb_dXdYdH	r = Reduction to the pole g = Total horizontal derivative b = Total horizontal derivative
(1, 2, 3)_MAF/MTF_rgb_TDRTDRdHTDRdH	r = Tilt derivative g = Total horizontal derivative of tilt derivative b = Total horizontal derivative of tilt derivative

Table 4-4. File description, VLF grids and processed files in arc ascii grid formats.

Filename	Description
VLF_Totf_12I_N_40×40 m **VLF_Totf_12I_S_40×40 m**	VLF, Total field (transmitter GBR) 12I Östhammar North and South 40×40 m nearest neighbour grid, SGU1982
FMBE_VLF_Totf_V1_40×40 m **FMBE_VLF_Totf_V2_40×40 m** **FMBE_VLF_Resistivity**	VLF, Total field (1st transmitter) 40×40 m nearest neighbour grid VLF, Total field (2nd transmitter) 40×40 m nearest neighbour grid VLF, resistivity, 40×40 m maximum likelihood grid 13I Österlövsta, SGU 1998, selection FMBE = flight identity

Table 4-5. File description, data coverage areas.

Filename	Description
Fm_NGU_ns_MagnArea_region.shp	Forsmark PLU, 2002, NGU airborne geophysical survey, NS survey direction
MFM_2019_DataAcquisitionArea_region.shp	Data acquisition area for this work
SGU_1982_VLF_Oneway_region.shp	SGU 1982, airborne geophysics, VLF, 12I Östhammar
SGU_1998_VLF_Twoway_resistivity_region.shp	SGU 1998, airborne geophysics, VLF, 13I Österlövsta, data acquisition area selection
MFM_2019_SKB_DEM_20m_rectangle.shp	Digital elevation model, 20×20 m grid, delivered by SKB, Nov-2019

Table 4-6. File description, interpretation data.

Filename	Description
MFM_3km_Merge_2019_and_RMA_ linked_lineament_line.shp	Linked lineaments from this work. Length > 3 km. Merged with previous linked lineaments, version 2.2 (polyline)
MFM2019_3km_WorkArea_2019_method-specific_lineament_line.shp	Method-specific/co-ordinated, magnetic lineaments from this work (polyline). Length > 3 km
MFM_2019_DisturbedArea_region.shp **MFM_2019_DisturbedArea_line.shp**	Magnetically disturbed area from the Fenno-Skan DC cable (polyline and region)
MFM_2019_WorkArea_region.shp	Interpretation work area (region)

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Appendix 1

Lineament attribute table.

Field name	Name	Description	Attribute used to describe lineaments
Id_t	Identity	Identity of a linked lineament	ID-number according to SKB (MFMxxxx). Assigned only for linked lineaments. Not previously identified lineaments start with MFM3500
Origin_t	Origin	Major type of basic data	Basic data or Method specific or Coordinated lineaments
Class_t	Classification	Classification of a coordinated lineament	Regional (> 10 km), local major (1–10 km) and local minor (< 1 km) lineaments (Andersson 2003). Valid only for linked lineaments
Method_t	Method	The type of data in which the observation is identified	Magnetics (Magn)
Weight_n	Weight	This assessment is based on both the number of properties upon which the lineament has been identified and the degree of uncertainty. An overall indication of the confidence of a lineament	Graded from 1 = low weight to 5 = high weight for Method specific or Coordinated lineament. A weighted average according to the length of each segment in a linked lineament. Valid only if more than one method is interpreted. See also Section 2.3.1.
Char_t	Character	Character of the observation in letters	Method characteristics like minima, edge, minima connection or Coordinated or Linked lineament
Char_n	Character	Character of the observation translated to an integer	1 = minima or edge, 0 = minima connection A weighted average has been calculated according to the length of each segment in the linked lineament
Uncert_t	Uncertainty	Gradation of identification, in terms of uncertainty. In effect, this attribute involves both the degree of clarity of the lineament as well as a judgement regarding the possible cause of the lineament	1 = low, 2 = medium, 3 = high A weighted average has been calculated according to the length of each segment in the linked lineament
Comment_t	Comment	Specific comments to the observation	”text, text, text”
Process_t	Processing	Data processing carried out	Grid, filter, image analysis, GIS
Date_t	Date	Point of time for interpretation	Date
Scale_t	Scale	Scale of interpretation	50 000/20 000/10 000
Width_t	Width	Width on average	Not assigned in this work
Precis_t	Precision	Spatial uncertainty of position. An estimate of how well the lineament is defined in space	Mostly around 50 m in this work
Count_n	Count	The number of original segments along the lineament	Always 1 for a method specific lineament
Cond_n	Conductivity	Shows how much of the lineament that has been identified by EM and/or VLF	A weighted average has been calculated, according to the length of each segment in the linked lineament. 0.00–1.00 = 0–100 %. When only magnetic lineaments are concerned, always 0
Magn_n	Magnetic	Shows how much of the lineament that has been identified by magnetics	A weighted average has been calculated, according to the length of each segment in the linked lineament. 0.00–1.00 = 0–100 %. When only magnetic lineaments are concerned, always 1

Field name	Name	Description	Attribute used to describe lineaments
Topo_n	Topography	Shows how much of the lineament that has been identified by topography, either in the ground surface or in the rock surface	A weighted average has been calculated, according to the length of each segment in the linked lineament. 0.00–1.00 = 0–100 %. When only magnetic lineaments are concerned, always 0
Topog_n	Ground surface	Shows how much of the lineament that has been identified by topography in the ground surface	Not applicable in this work
Topor_n	Rock surface	Shows how much of the lineament that has been identified by topography in the bedrock surface	Not applicable in this work
Prop_n	Property	Shows in average, how many properties that identifies the lineament	A weighted average has been calculated, according to the length of each segment in the linked lineament. 0.00–1.00 = 0–100 %. When only magnetic lineaments are concerned, always 1
Length_n	Length	The length of the lineament	In metres
Direct_n	Direction	The average trend of the lineament	In degrees [°]
Platform_t	Platform	Measuring platform for the basic data	
Sign_t	Signature	Work carried out by	GeoVista AB/hi (Hans Isaksson), lj (Linnéa Johansson)

Arkitektkopia AB, Bromma, 2020

SKB is responsible for managing spent nuclear fuel and radioactive waste produced by the Swedish nuclear power plants such that man and the environment are protected in the near and distant future.

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