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A comparison of two independent interpretations of lineaments from geophysical and topographic data at the Forsmark site

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March 2005

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Keywords: Forsmark, site investigation, Lineament interpretation, Coordinated lineaments, Linked lineaments, Airborne geophysics, Topography.

This report concerns a study which was conducted for SKB. The conclusions and viewpoints presented in the report are those of the author and do not necessarily coincide with those of the client.

Abstract

In the development of site descriptions, uncertainties in the modelling work are given much attention. One aspect of this is the development of alternative models. Given the importance of the lineaments for the continued deformation zone modelling, it has been regarded important to carry out an alternative, independent lineament interpretation at the Forsmark site.

The objective of the work presented in this report was to compare the primary and alternative interpretations, which have been provided by two independent groups of geoscientists. A primary interpretation has been carried out by GeoVista AB and an alternative interpretation (within the central part of the site investigation area) by the Geological Survey of Finland (GTK). Based on the results of this comparative study, further evaluation of the inferred lineaments and the need for supplementary information are discussed.

When the two sets of inferred lineaments are compared, it must be remembered that the two groups have performed the interpretation work under different conditions. GeoVista AB has a profound knowledge of the geological setting, as opposed to GTK which has been provided only with some basic geological information. The different conditions might very well have affected some of the expert judgements involved in the interpretation process.

However, the comparison of the two independent lineament interpretations has revealed that the results are, in principle, reproducible. Nevertheless, there are discrepancies that are judged to be significant and have to be considered during the further assessment of lineaments.

The attributes assigned to the inferred lineaments provide an excellent tool for displaying the characteristics of an individual lineament. However, the use of a single attribute or a combination of attributes as a stand-alone criterion for the assessment can be seriously misleading. Whether a lineament represents a deformation zone or not must instead be concluded on the basis of all available data from outcrop observations, trenching, drilling, ground geophysics et cetera. When necessary, new such data must be acquired. The assessment should also include a revision of the whole interpretation process (method specific interpretation, coordination and linking of lineaments).

Sammanfattning

Vid utarbetandet av platsbeskrivningar läggs stor vikt på värdering av osäkerheter i modelleringsarbetet och en aspekt på detta är upprättandet av alternativa modeller. Eftersom tolkade lineament utgör ett betydelsefullt underlag för den fortsatta modelleringen av deformationszoner har det bedömts viktigt att genomföra en alternativ lineamentstolkning i Forsmarksområdet.

Syftet med det arbete som presenteras i denna rapport var att jämföra de primära och alternativa lineamentstolkningar som utförts av två oberoende grupper av geovetare. Den primära tolkningen har utförts av GeoVista AB och en alternativ tolkning (av ett begränsat område) av Geologiska forskningscentralen (GTK) i Finland. Utifrån resultaten av denna jämförelse diskuteras förutsättningarna för vidare utvärdering av lineamenten samt behov av kompletterande information.

När tolkningarna jämförs är det viktigt att komma ihåg att de bägge grupperna arbetat under delvis skilda förutsättningar. GeoVista AB har, efter att ha arbetat under lång tid i området, en ingående kunskap om de geologiska förhållandena medan GTK bara haft tillgång till mer översiktlig geologisk information. Detta kan mycket väl ha påverkat vissa bedömningar som gjorts under tolkningsprocessen.

Jämförelsen av de bägge tolkningarna visar emellertid att resultaten är i princip reproducerbara men att det trots allt finns vissa betydelsefulla skillnader som måste beaktas vid den fortsatta utvärderingen av lineamenten.

De attribut som har ansatts de tolkade lineamenten utgör ett utmärkt hjälpmedel för att visualisera lineamentens egenskaper. Däremot kan användande av enskilda attribut eller kombination av attribut för vidare utvärdering av lineamenten vara kraftigt vilseledande. Slutsatser om huruvida ett lineament representerar en deformationszon eller ej måste istället baseras på all tillgänglig information från hällobservationer, grävning, borrning, markgeofysik etcetera. När så behövs måste kompletterande undersökningar av denna typ göras. Utvärderingen skall också omfatta en genomgång av hela tolkningsprocessen (metodspecifik tolkning samt koordinering och länkning av lineament).

Contents

1 Introduction

SKB performs site investigations for localization of a deep repository for high level radioactive waste. The site investigations are performed at two sites, Forsmark and Simpevarp. Lineament interpretation from topographic and airborne geophysical data, outlining e.g. possible deformation zones, is an essential part of the investigations at both sites.

One component in the characterisation work is the development of a site descriptive model that constitutes an integrated description of the site and its regional setting, covering the current character of the geosphere and the biosphere as well as the ongoing natural processes that affect their long-term evolution.

At the Forsmark site, GeoVista AB has been commissioned by SKB to carry out extensive lineament interpretations, not only as part of the site investigations but also during the preceding regional study of the Uppsala county and the feasibility study of the Östhammar municipality.

The assessment of the inferred lineaments gave rise to some questions, mainly concerning

i) the reproducibility of the interpretations,

ii) the lineaments relation to deformation zones or other features of importance to the site characterisation.

In the development of the site descriptions, uncertainties in the modelling work have been and will continue to be given much attention. One aspect of this is the development of alternative models. Given the importance of the lineaments for the continued deformation zone modelling, it was regarded important to carry out an alternative, independent lineament interpretation using another team, in order to explore the sensitivity to "modelling style".

The Geological Survey of Finland (GTK) was asked to perform this alternative interpretation of lineaments. The alternative interpretation also broadened the basis for a discussion of the relationship of lineaments to deformation zones. Both items are treated in the present report.

2 Objective and scope

The objective of the work was to

i) compare the primary (GeoVista AB) interpretation with the alternative (GTK) interpretation,

ii) discuss the geological interpretation and further investigations of the lineaments.

The GeoVista AB interpretation covers a much larger area but the comparison is made within the restricted sub-area interpreted by GTK, see Figure 2-1. The GTK area covers the central part of the site investigation area, including the Forsmark candidate area.

Based on the results of the comparative study and on the present knowledge of the Forsmark area, further evaluation of the inferred lineaments and the requirements for supplementary information are discussed.

It should be noted that the present work did not aim at any assessment of the quality or any ranking of the two interpretations.

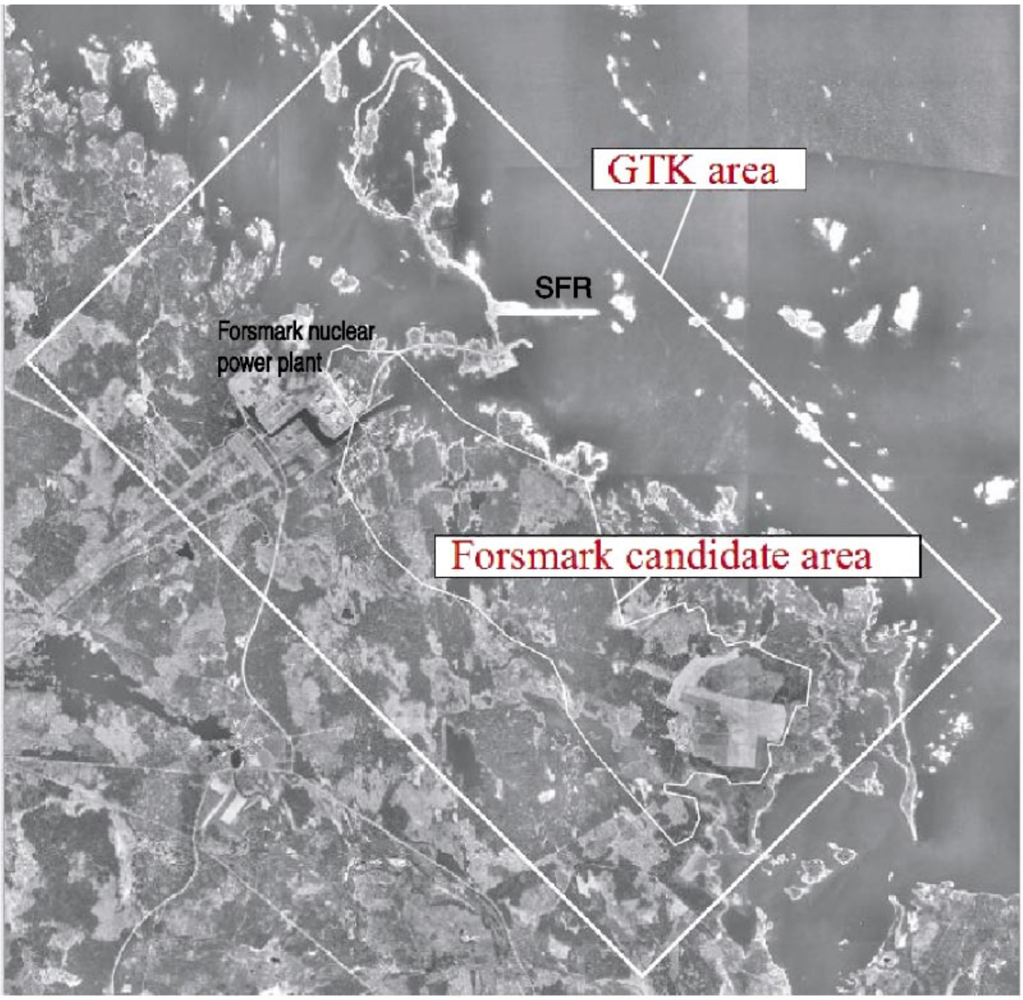

__Figure 2-1.__ The GTK interpretation area, covering the Forsmark candidate area and the near surroundings. The approximate projected position of the SFR underground facilities is also shown.

3 Lineament interpretations carried out

A lineament is a linear anomaly on the Earth's surface, straight or gently curved, which has been interpreted on the basis of a 2-dimensional data set, such as a topographic map, a digital terrain model (DTM), an air photo mosaic, or an aeromagnetic map. A lineament can, but does not necessarily indicate a geological structure, such as a deformation zone, a dyke rock, or an esker. Lineaments are qualified according to their origin (i.e. the method or data base which led to their definition), for instance, topographic lineaments, magnetic lineaments, etc /Munier et al. 2003/.

Prior to the site investigations, lineament interpretations have been carried out in the Forsmark area and the surrounding region as part of the regional study of the county of Uppsala /Antal et al. 1998/ and the feasibility study of the Östhammar municipality /Bergman et al. 1996, 1998/.

Several other scientific works related to lineament interpretation and structural modelling have been carried out in the SFR – Forsmark area, notably /Axelsson and Hansen, 1987/ and /Tirén et al. 2002/.

The present study is focused on the lineament interpretations performed during the site investigation phase. These interpretations are based on the more detailed topographic data /Wiklund, 2002/ and airborne geophysical data /Rønning et al. 2003/ acquired during the initial phase of the site investigation. The airborne geophysical data comprise magnetics, EM (dipole source and VLF) and radiometrics. However, the radiometric data have not been used for lineament interpretation.

The most extensive lineament interpretation in the Forsmark area has been carried out by GeoVista AB and is hereafter referred to as the primary interpretation (or GeoVista interpretation) as opposed to the alternative interpretation (or GTK interpretation).

3.1 Primary lineament interpretation

The primary interpretation, guided by the method descriptions ”Metodbeskrivning för lineamentstolkning baserad på topografiska data” /SKB, 2002a/ and “Metodbeskrivning för tolkning av flyggeofysiska data” /SKB, 2002b/, has been carried out in three phases:

The first phase included interpretation of lineaments from topographic data /Isaksson, 2003/ and covers the land area.

The second phase interpretation was carried out from airborne geophysical data (magnetic, dipole source EM and VLF EM) and integrated with the phase 1 topographic interpretation /Isaksson et al. 2004/. The interpretation covers the main land area.

In the third phase, bathymetric data and results from an inversion of airborne electromagnetic data in the coastal and open sea area were interpreted /Isaksson and Keisu, 2004/. Also older seismic surveys from the Forsmark nuclear power plant and SFR areas were interpreted /Isaksson and Keisu, 2004/. The results were fully integrated with the phase 2 results and the phase 3 results therefore represent a complete lineament interpretation of the Forsmark area.

The methodology and results are documented by /Isaksson, 2003/, /Isaksson et al. 2004/ and /Isaksson and Keisu, 2004/. A brief summary of the interpretation methodology is presented in the following section. The phase 1 topographic interpretation was made according to step 1 of this methodology.

3.1.1 Methodology for integrated lineament interpretation

The method of lineament interpretation follows a step-by-step procedure:

Step 1 involves the interpretation of topography, magnetics and EM (dipole source and VLF) separately and each "method specific lineament" is characterised by a set of attribute data.

Step 2 includes coordination of the method specific lineaments into "coordinated lineaments" and the discriminating methods for each lineament are added as attribute data. The length of each lineament is also calculated. A weight attribute is added to illustrate the confidence of the lineaments. The coordination of lineaments is illustrated by Figure 3-1.

In step 3, the coordinated lineaments are linked together. The comprehensive attribute table facilitates further statistical analysis and scrutiny of the linked lineaments as possible deformation zones. The linking process is illustrated by Figure 3-2 and Table 3-1 shows the attribute table used for the linked lineaments interpreted during phase 2 of the investigations.

Optionally, based on surface geological data, drilling or other ground truth data, a lineament or parts of a lineament can be upgraded to a deformation zone (step 4). This was carried out during the phase 2, but not the phase 3 interpretation.

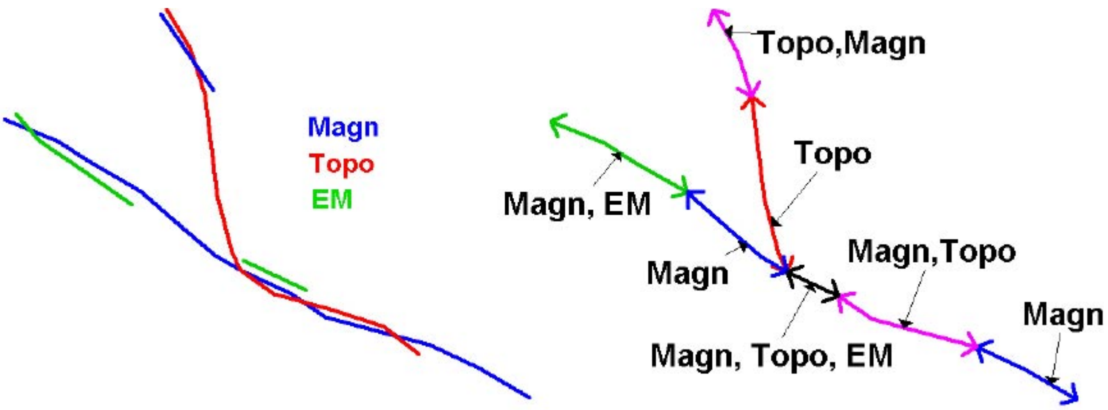

Figure 3-1. Lineament coordination. Method specific lineaments; magnetic, topographic and EM in blue, red and green, respectively, to the left. From /Isaksson and Keisu, 2004/.

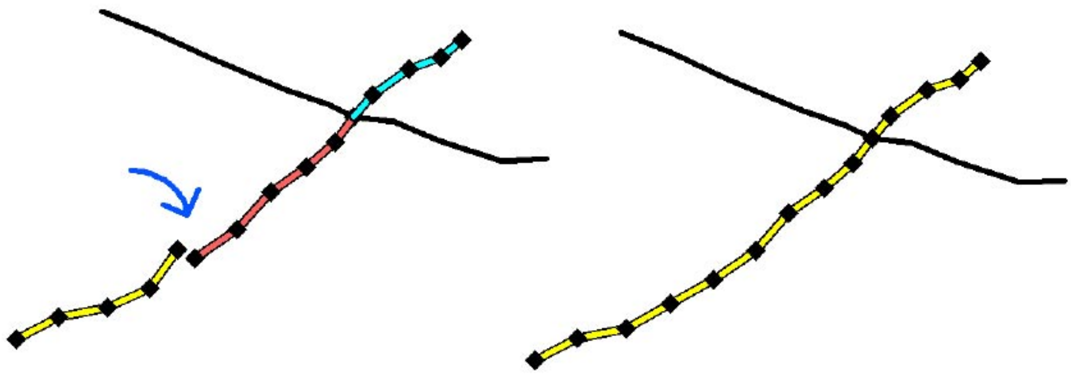

Figure 3-2. *Linking of lineaments, including node adjustment (blue arrow). From /Isaksson and Keisu, 2004/.*

Table 3-1. Attribute table for (phase 2) linked lineaments. After /Isaksson et al. 2004/.

Field name	Name	Description	Attribute used to describe lineaments
Id_t *	Identity	Identity of the lineament.	ID-number according to SKB (XFM……).
Origin_t	Origin	Major type of basic data.	Coordinated lineaments.
Class_t **	Classification	Classification of the lineament.	Regional (> 10 km), local major (1–10 km) and local minor (<1 km) lineaments.
Weight_n **	Weight	A combination of uncertainty and number of properties (methods). An overall assessment of the confidence of the linked lineament. This assessment is based on both the number of properties upon which the lineament has been identified and the degree of uncertainty.	A weighted average, graded continuously from 1 = low quality to 5 = high quality, has been calculated, according to the length of each segment in the linked lineament.
Char_t **	Character	Character of the observation.	Linked lineament.
Uncert_t	Uncertainty	Gradation of identification, in terms of uncertainty. In effect, this attribute is an expert judgement concerning the degree of clarity of the lineament.	An estimate of uncertainty of the linked lineament, graded as 1 = low, 2 = medium and 3 = high. A weighted average, 1.00–3.00, has been calculated according to the length of each segment of the linked lineament.
Comment_t	Comment	Specific comments to the observation.	
Process_t	Processing	Data processing performed.	Image analysis, GIS.
Date_t	Date	Point of time for interpretation.	Date.
Scale_t	Scale	Scale of interpretation.	10,000–20,000, 50,000.
Precis_t	Precision	Spatial uncertainty of position. An estimate of how well the lineament is defined in space.	10–100 m.
Count_n	Count	The number of original segments along the linked lineament.	Integer.
Cond_n	Conductivity	Shows how much of the lineament that has been identified by EM and/or VLF.	0.00–1.00 = 0–100%. A weighted average has been calculated, according to the length of each segment, for the linked lineaments.
Magn_n	Magnetic	Shows how much of the lineament that has been identified by magnetics.	0.00–1.00 = 0–100%. A weighted average has been calculated, according to the length of each segment for the linked lineaments.
Topo_n	Topography	Shows how much of the lineament that has been identified by topography.	0.00–1.00 = 0–100%. A weighted average has been calculated, according to the length of each segment for the linked lineaments.

Field name	Name	Description	Attribute used to describe lineaments
Prop_n **	Property	Shows how many properties that has been identified the lineament.	1.00–3.00. A weighted average has been calculated, according to the length of each segment for the linked lineaments.
Length_n	Length	The length of the lineament.	
Direct_n	Direction	The average trend of the lineament.	0–360 degrees
Platform_t	Platform	Measuring platform for the basic data.	Airborne geophysics 30–60 m altitude, air photos from 2,300 m altitude
Sign_t	Signature	Work performed by	e.g. hi (Hans Isaksson), GeoVista AB

*) GTK assigned a GTK-identity (LL…) to the linked lineaments
**) Not assigned by GTK

3.2 Alternative lineament interpretation

Within a limited area, see Figure 2-1, an alternative lineament interpretation has been carried out by the Geological Survey of Finland (GTK) and documented by /Korhonen et al. 2004/. GTK was instructed to apply the same methodology as the one used for the primary interpretation. However, a number of attributes; Identity (SKB identity of linked lineament), Classification (classification of lineament group), Property (how many properties have identified the lineament), and Weight (a combination of the property and uncertainty attributes) were, in accordance with given instructions, not assigned by GTK.

The alternative interpretation was performed at the time when the phase 2 primary interpretation was completed and phase 3 ongoing. It was decided that the alternative interpretation should be compared to the phase 2 primary interpretation. Consequently, neither the bathymetric data from a marine geology survey nor the inverted helicopter EM data that were used in the phase 3 primary interpretation were provided to GTK. Furthermore, the bathymetric data set is classified for military defence reasons and could, therefore, not be made available to GTK.

4 Comparison of the primary and alternative interpretations

The comparison of the phase 2 primary interpretation with the alternative interpretation is made by first comparing the method specific lineaments and then the linked lineaments.

The linked lineaments constitute the final product of the lineament interpretation and are the most important ones to study. However, since the linked lineaments are constructed by the process of coordinating and linking the method specific lineaments, it is also important to study this first step of the interpretation process.

The coordination of lineaments includes, among other things, decision-making on which method should be used to outline the lineament in those cases when e.g. the topographic and magnetic lineaments are slightly displaced but still interpreted as one lineament. The coordination process is difficult to review in a generalised way and left out of this study. Instead, this is recommended to be a part of the further assessment of the inferred lineaments as discussed in Chapter 5.

4.1 Topographic lineaments

Figure 4-1 shows the primary (GeoVista) interpretation and Figure 4-2 the alternative (GTK) interpretation superimposed on the topographic map (the digital terrain model). Figure 4-3 shows the two interpretation sets together.

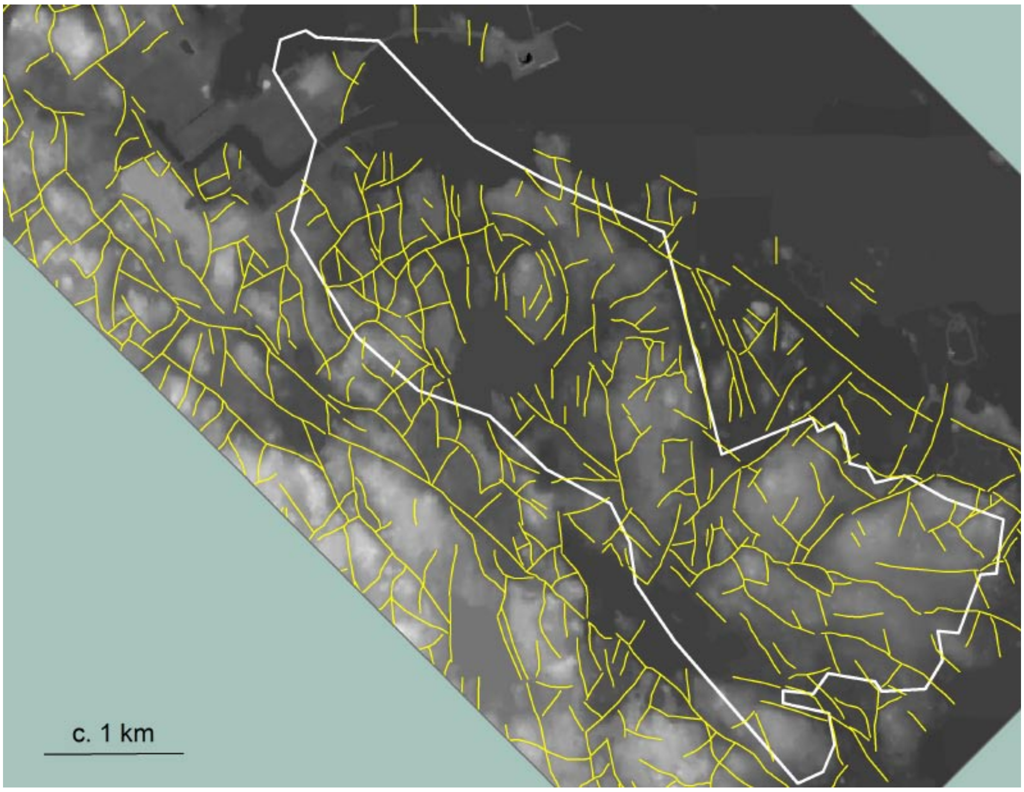

Figure 4-1. *The primary (GeoVista) interpretation of topographic lineaments (yellow) superimposed on a grey scale presentation of the digital terrain model.*

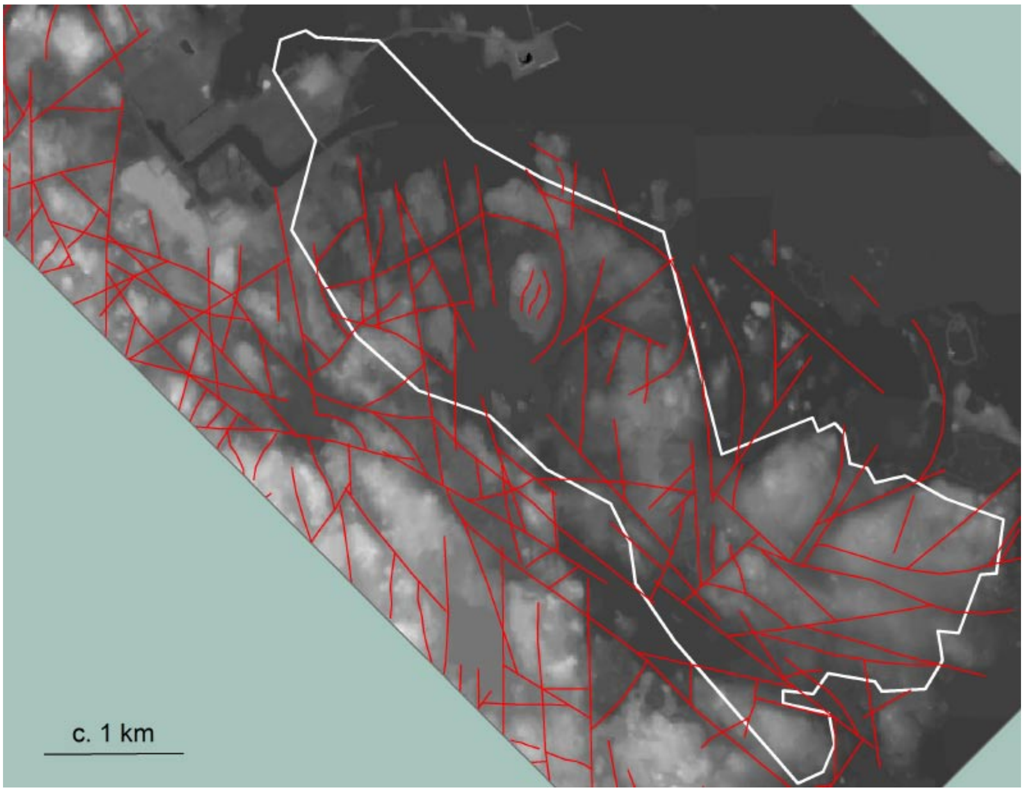

Figure 4-2. The alternative (GTK) interpretation of topographic lineaments (red) superimposed on a grey scale presentation of the digital terrain model.

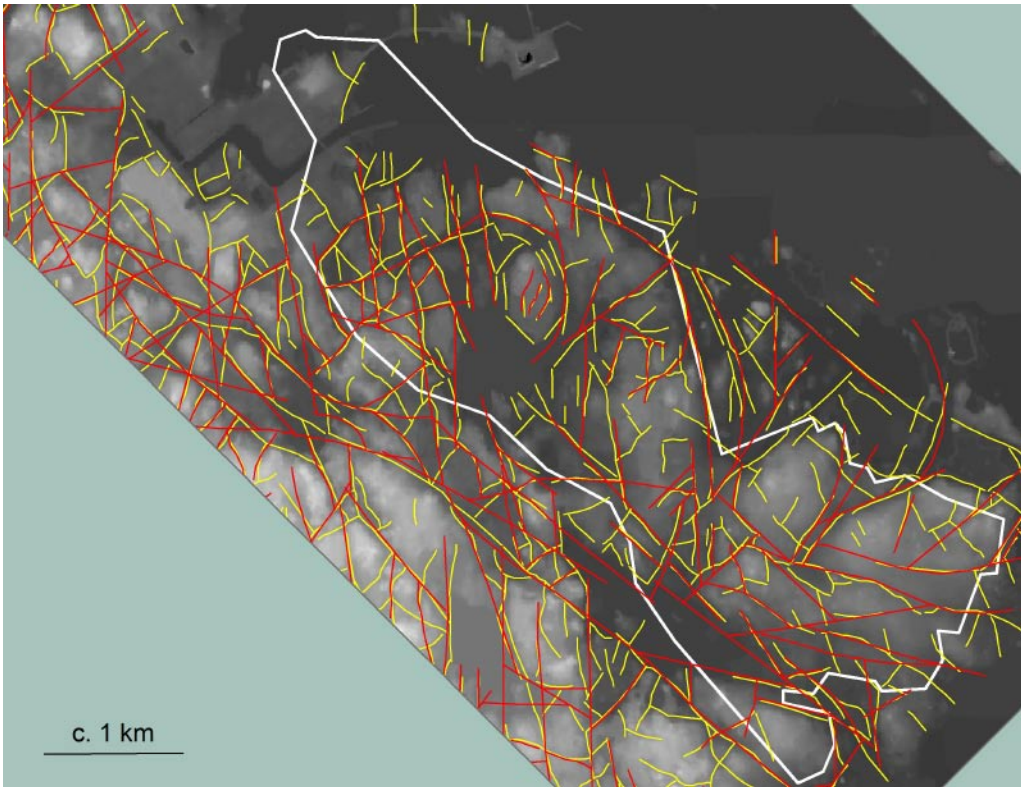

Figure 4-3. Topographic lineaments superimposed on a grey scale presentation of the digital terrain model. The primary (GeoVista) interpretation in yellow and the alternative (GTK) interpretation in red.

When comparing the interpretations it can be noted that the GeoVista version is more detailed in the sense that the lineaments follow the topographic features more "carefully" and that comparatively shorter lineaments are included.

The GTK version contains longer lineaments, generally outlined as straight lines. Small-scale topographic features (slopes) in areas of assumed thick overburden have not been included since they were judged not to be related to deformation zones /Korhonen et al. 2004/.

When studied together, Figure 4-3, the two interpretations appear similar. The more persistent lineaments do frequently coincide and the major difference is the one discussed above. The reason for arriving at slightly different results is probably a combination of deviating "interpretation philosophy" and the time spent on the work. The GTK interpretation was made within a more restricted time frame.

4.2 Magnetic lineaments

Figure 4-4 shows the primary (GeoVista) interpretation and Figure 4-5 the alternative (GTK) interpretation superimposed on the magnetic map. Figure 4-6 shows the two interpretation sets together.

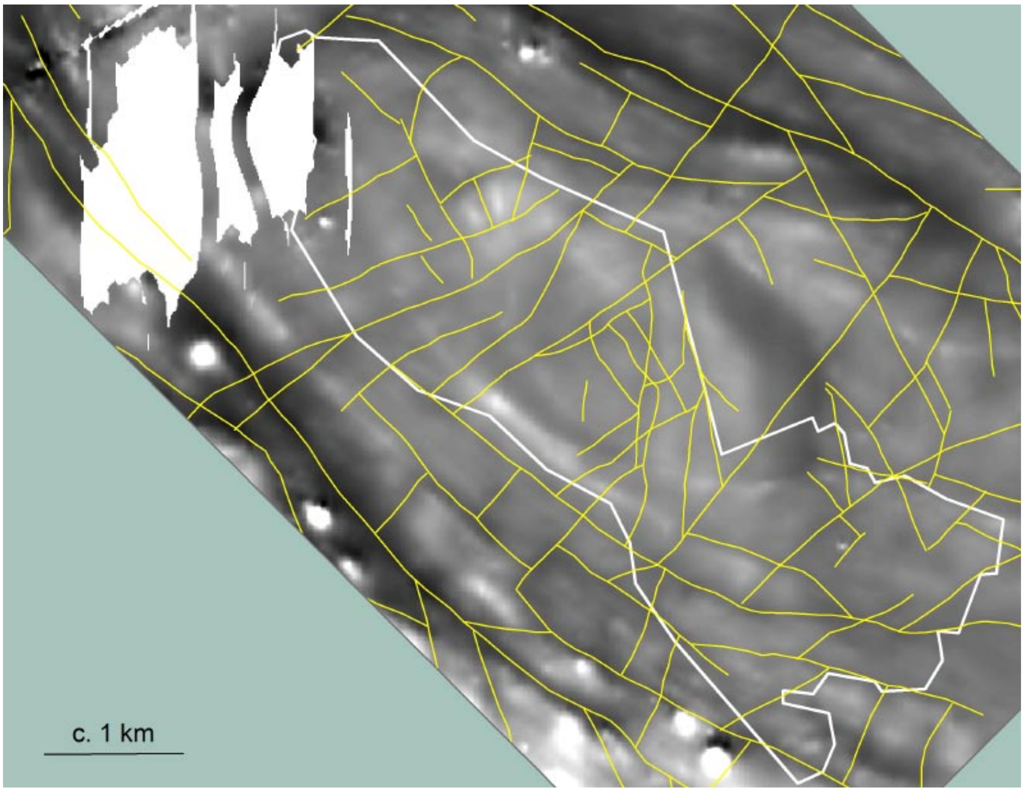

Figure 4-4. *The primary (GeoVista) interpretation of magnetic lineaments (yellow) superimposed on a grey scale presentation of the magnetic anomaly.*

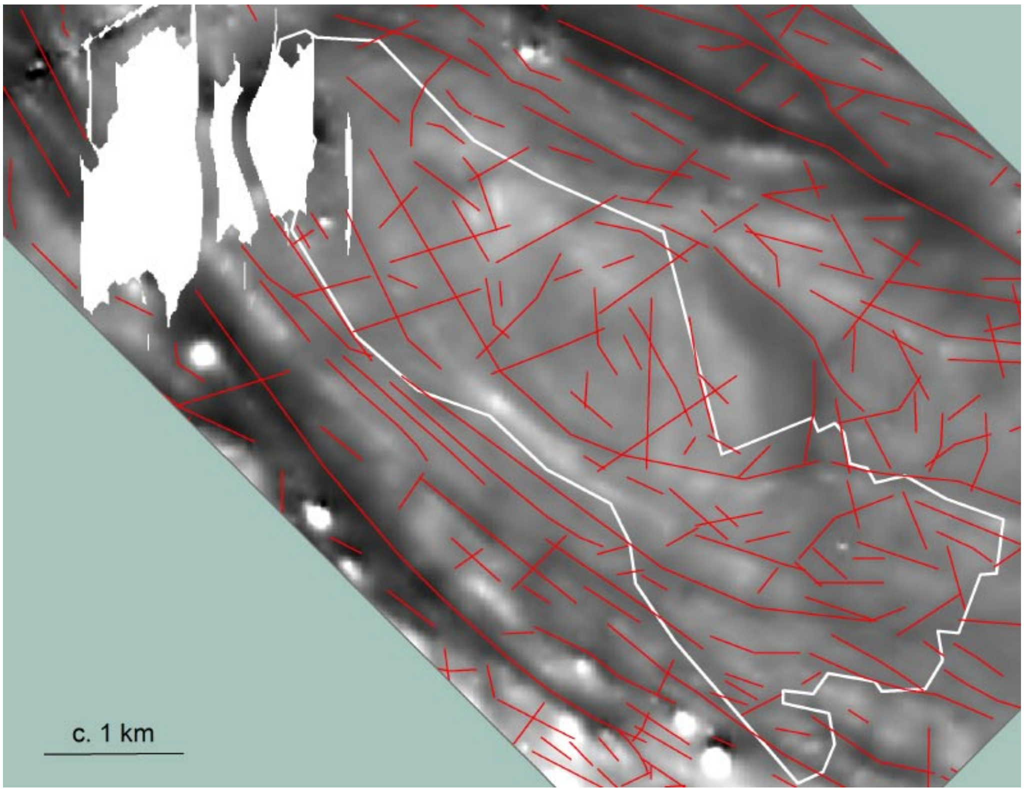

Figure 4-5. *The alternative (GTK) interpretation of magnetic lineaments (red) superimposed on a grey scale presentation of the magnetic anomaly.*

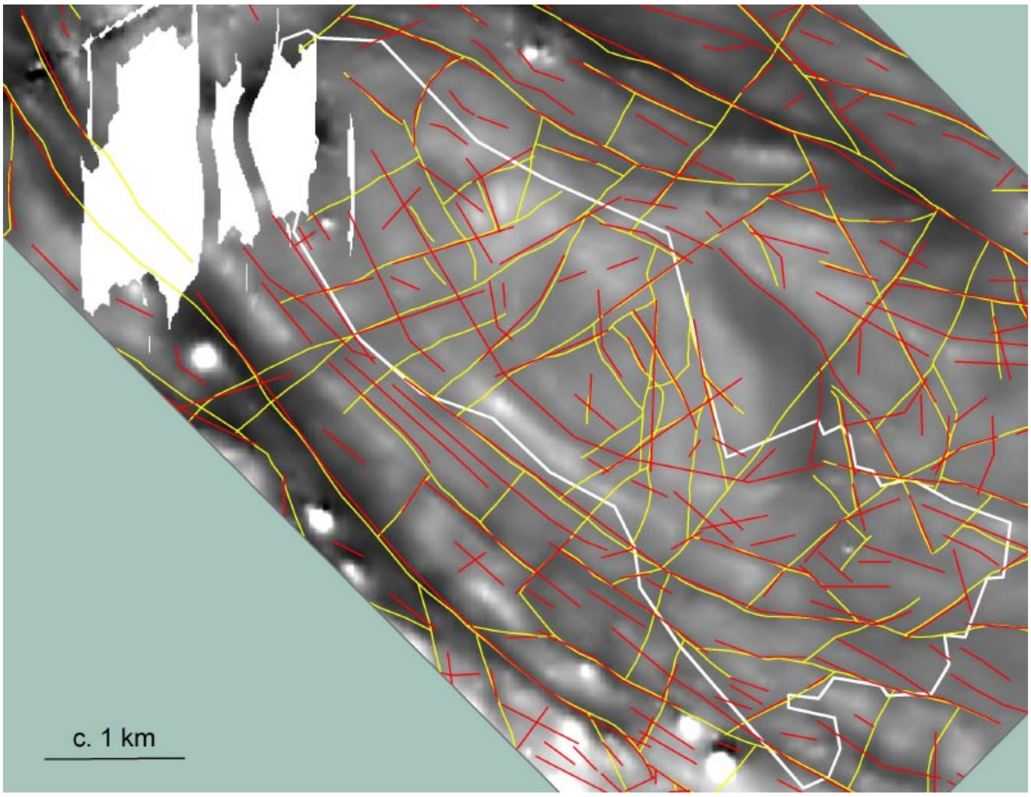

Figure 4-6. *Magnetic lineaments superimposed on a grey scale presentation of the magnetic anomaly. The primary (GeoVista) interpretation in yellow and the alternative (GTK) interpretation in red.*

The two magnetic interpretations differ notably in style. The GeoVista lineaments generally tend to be truncated by another lineament, thus forming a pattern of closed polygons. This pattern has in some cases been formed by extending lineaments through minor areas of diffuse magnetic anomalies. The GTK lineaments represent a more conservative approach in the sense that lineaments generally have been outlined only when they are more well-defined. However, the general impression is that the two sets of lineaments coincide well, especially regarding the more persistent lineaments. Coinciding NW trending lineaments appear to the NE and SW of the Forsmark candidate area and many NE trending lineaments crossing the whole area under discussion are also coincident.

Nevertheless, it is important to note a few important discrepancies. Immediately to the SW of the candidate area, there is a number of NW trending GTK lineaments of which at least two are not found among the GeoVista lineaments. Furthermore, within the candidate area appears a consistent GTK lineament again not presented by GeoVista. In both cases, GeoVista has interpreted magnetic lows as caused by low magnetic lithological units or banding (see also the interpretation of magnetic patterns in /Isaksson et al. 2004/). GTK instead indicates possible deformation zones which in itself does not oppose the zones also representing lithological contacts or banding. Finally, there are a limited number of generally NE trending GeoVista lineaments, which do not appear among the GTK lineaments.

4.3 Electromagnetic lineaments

Figure 4-7 shows the primary (GeoVista) and alternative (GTK) interpretations of the dipole source EM data superimposed on the apparent resistivity (800 Hz) map. Note that the GeoVista lineaments in the sea area are preliminary and based on AGC filtered helicopter EM data. This data was later exchanged for inversion results, which were not available to GTK. Figure 4-8 shows the primary (GeoVista) and alternative (GTK) interpretations of VLF data superimposed on the ortho station total field data.

The EM, both dipole source and VLF, data are much affected by cultural noise, e.g. power lines, and this has made the interpretation highly uncertain in some areas. Hence, the frequency of high uncertainty EM lineaments is considerably higher when compared to the magnetic and topographic lineaments. GTK reports 66% high uncertainty dipole-source lineaments and 89% high uncertainty VLF lineaments. This should be compared to the corresponding figures for magnetic and topographic lineaments, which are 46% and 41%, respectively. GeoVista reports (for the whole land area) similar results, 70%, for diple source EM but a much lower figure, 37% for VLF.

In the light of the circumstances mentioned, it is still encouraging to note that at least many longer lineaments coincide with each other. These lineaments show zones of increased electrical conductivity and may, with great caution, be looked upon as an indication of water-bearing deformation zones.

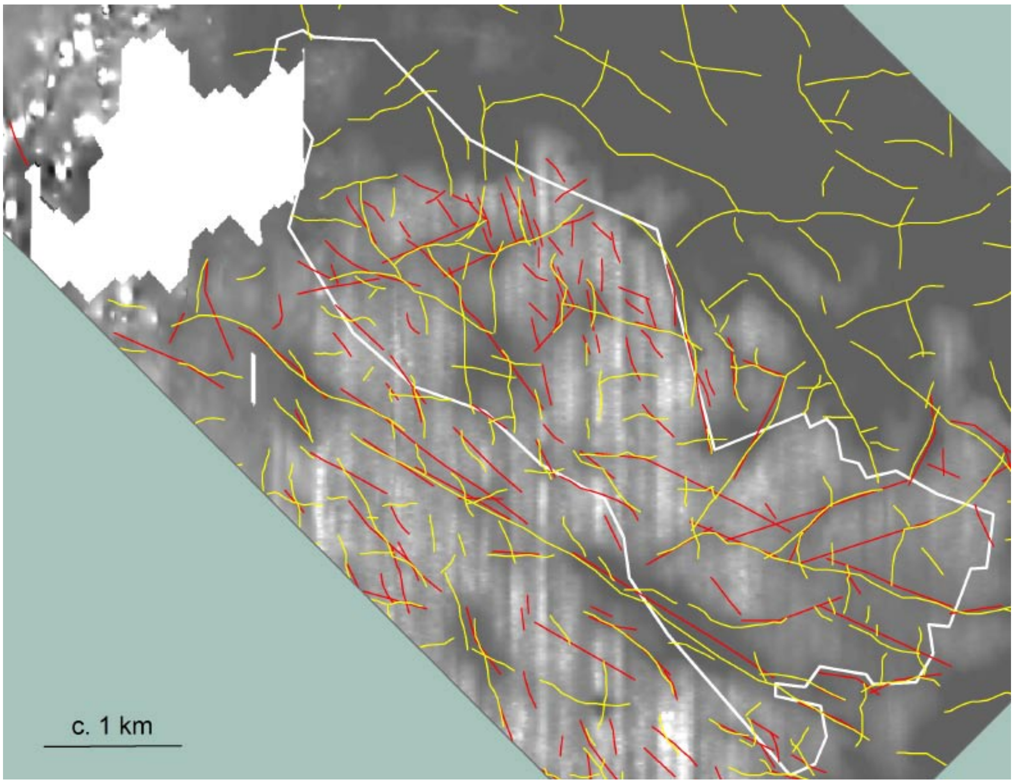

Figure 4-7. *Electromagnetic (dipole source) lineaments superimposed on a grey scale presentation of the apparent resistivity (800 Hz) map. The primary (GeoVista) interpretation in yellow and the alternative (GTK) interpretation in red. The GeoVista interpretation in the sea area is preliminary and no corresponding interpretation was carried out by GTK.*

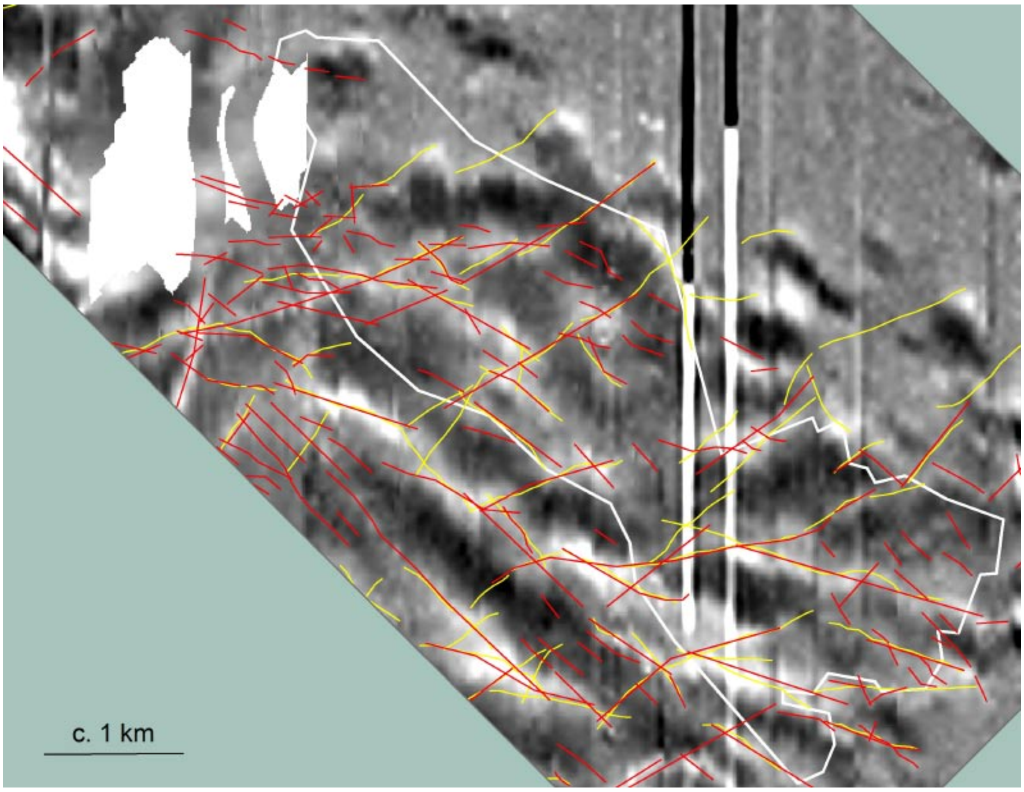

Figure 4-8. *VLF lineaments superimposed on a grey scale presentation of the VLF total field ortho station data. The primary (GeoVista) interpretation in yellow and the alternative (GTK) interpretation in red.*

4.4 Linked lineaments

The set of linked lineaments, Figure 4-9, is the final interpretation product. It is the result of method specific interpretation, coordination and linking of lineaments, and includes various expert judgements. The expert judgements become important since there are no objective criteria which can guide the coordination and linking of lineaments. It is therefore not surprising that the two sets of interpretation occasionally differ. Still, the majority of the longer lineaments forming the basic lineament pattern coincide well, although there is a number of inferred lineaments appearing in only one of the two interpretation sets.

When the longer lineaments differ in length or position, the discrepancies reflect differing method specific interpretations as well as differing judgements concerning coordination (which method specific lineament rules the outline of the coordinated lineament) and linking (when and how lineaments are linked). The interpretations of shorter lineaments, on the other hand, basically reflect different results (if the lineament is identified or not) from the method specific interpretations.

The linked lineaments are further discussed in the next section, which deals with their assigned attributes.

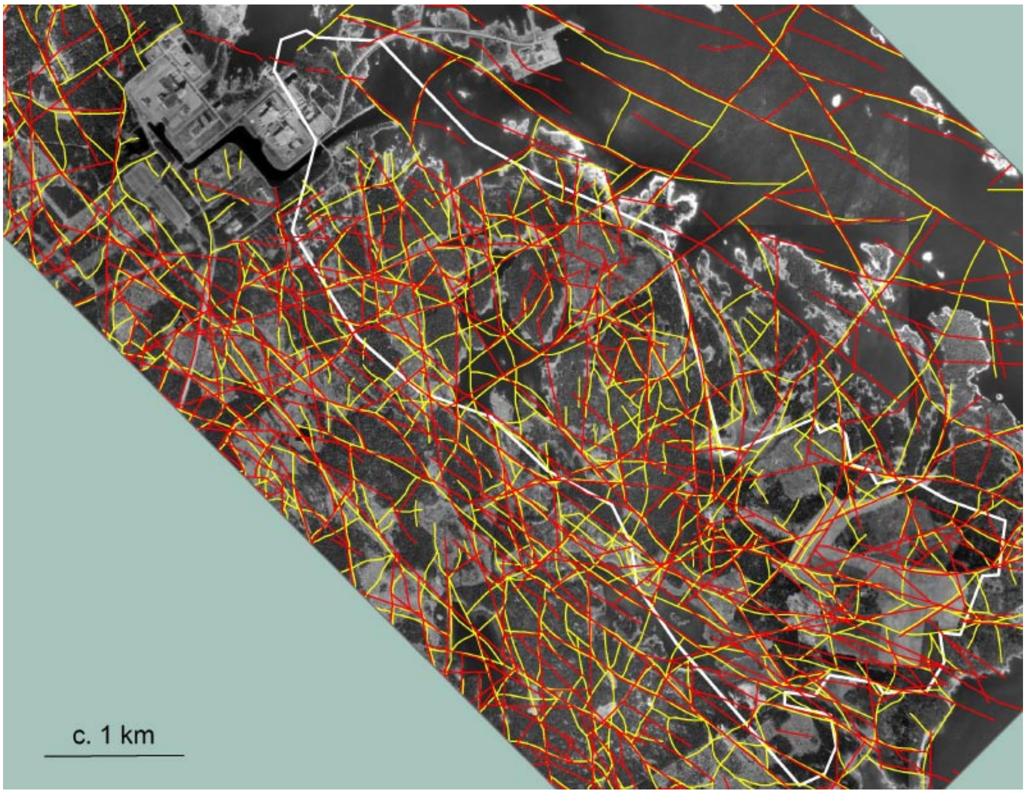

Figure 4-9. *Linked lineaments superimposed on a mosaic of grey scale orthophotos. The primary (GeoVista) interpretation in yellow and the alternative (GTK) interpretation in red.*

4.5 Linked lineament attributes

The set of attributes assigned to the lineaments, intended to facilitate further assessment work, is presented in Table 3-1. Table 4-1 presents some selected statistics concerning uncertainty and length of the linked lineaments as assigned by GeoVista and GTK.

It must be pointed out that the statistics is based on the GTK lineaments on one hand and the GeoVista lineaments intersecting the GTK interpretation area on the other. In practice, this means that the GTK lineaments are "truncated" (only interpreted to, or just outside, the area boundary) in all directions. Since the GeoVista interpretation area extends far beyond the GTK area to the NE and SW but coincides with the GTK area towards NW and SE, the GeoVista lineaments are truncated only towards NW and SE. However, this inherent bias is not considered to significantly influence the statistics presented.

Table 4-1. Attributes assigned to the interpreted linked lineaments.

Length Number of lineaments	All	< 500 m	500–999 m	1,000–2,999 m	> 3,000 m	Mean length
Primary interpretation	519	304 (59%)	121 (23%)	78 (15%)	16 (3%)	729
Alternative interpretation	514	224 (44%)	166 (32%)	113 (22%)	11 (2%)	819
Uncertainty **Number of lineaments**	**All**	**1.0–1.4**	**1.5–1.9**	**2.0–2.4**	**2.5–3.0**	**Mean uncertainty**
Primary interpretation	519	100 (19%)	44 (8%)	267 (52%)	108 (21%)	2.0
Alternative interpretation	514	87 (17%)	15 (3%)	169 (33%)	243 (47%)	2.3

Length

Although considerable differences exist between the length of method specific lineaments (cf Figure 4-1, 4-2 and 4-4, 4-5) the length distribution of the linked lineaments is remarkably similar. The coordination and linking process has neutralised the differences appearing in the method specific lineaments and produced a set of lineaments similar in length and style. Many lineaments are shorter than 500 m (59% GeoVista and 44% GTK) and lineaments longer than 1,000 m account for 18% of the GeoVista and 24% of the GTK lineaments. A few lineaments (2% and 3%, respectively) are longer than 3,000 m.

Figure 4-10 displays the two interpretation sets of linked lineaments which are longer than 1,000 m. The patterns are quite consistent but there are cases where the length of what appears to be the same lineament differs significantly between the two interpretation sets. This is most likely due to uncertainties concerning when and how to link the lineaments. To use the length attribute as a single criterion for the selection of lineaments for further assessment can therefore be misleading.

Uncertainty

The uncertainties assigned by GeoVista and GTK are equally distributed in the sense that more than 70% of the lineaments have been assigned an uncertainty > 2.0. The accumulations of values in the interval 2.0–2.4 (GeoVista) and 2.5–3.0 (GTK) are most likely less important.

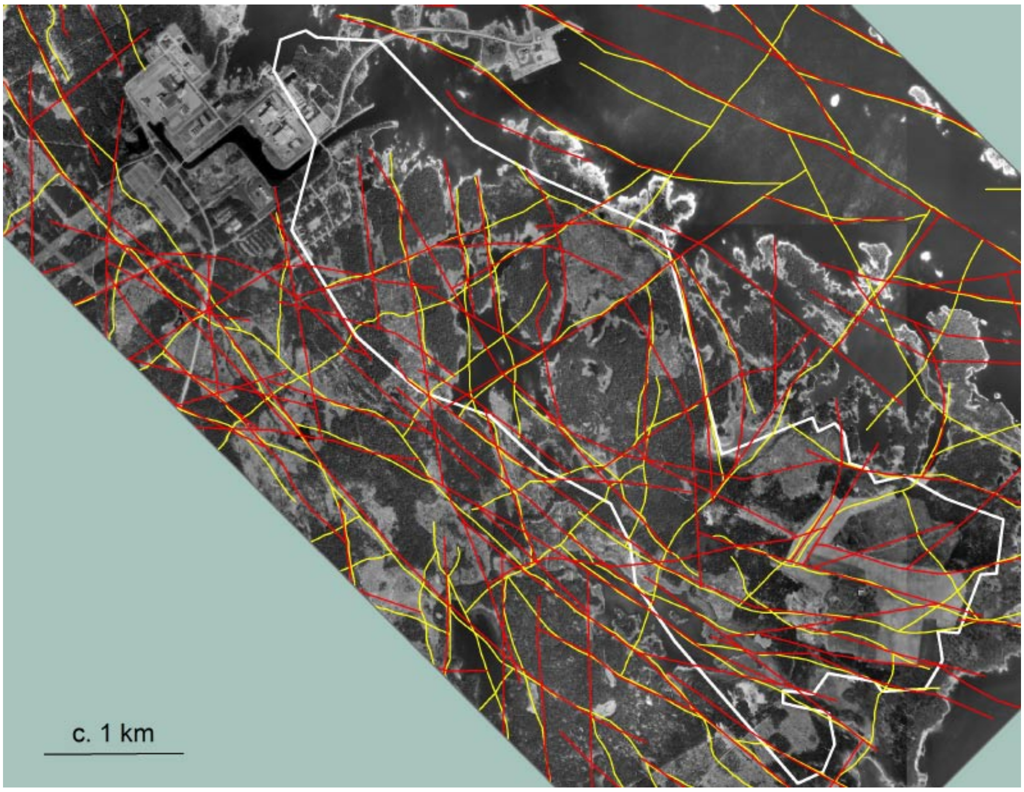

Figure 4-10. *Linked lineaments longer than 1,000 m, superimposed on a mosaic of grey scale orthophotos. The primary (GeoVista) interpretation in yellow and the alternative (GTK) interpretation in red.*

From the interpretations presented and from the accompanying reports, it can be questioned if the assigned uncertainty always refers only to the lineament as such, or sometimes also has been influenced by the assumed probability that the lineament defines a deformation zone.

Figure 4-11 displays the two interpretation sets of linked lineaments with uncertainty < 2.0. In parts of the area, the general pattern is consistent but in other parts not. This again calls for great caution when making use of a single criterion as an assessment tool.

Precision

The attribute "precision" is intended to indicate how well the lineament is defined in space (cf Table 3-1). The assigned GeoVista and GTK values differ considerably. While GeoVista has given fixed values (related to the interpretation scale according to principles presented in SKB, 2000a), GTK has frequently reported an interval (e.g. 10–15 m, 15–25 m).

The GeoVista linked lineaments have been assigned the precision of the method specific lineament (generally magnetic or topographic) which has been used to outline it. The assigned precision, consistently 20 m, corresponds to the value for the magnetic lineaments. The values for EM lineaments are 30 or 50 m and for the topographic lineaments 10, 20, 50 or 100 m.

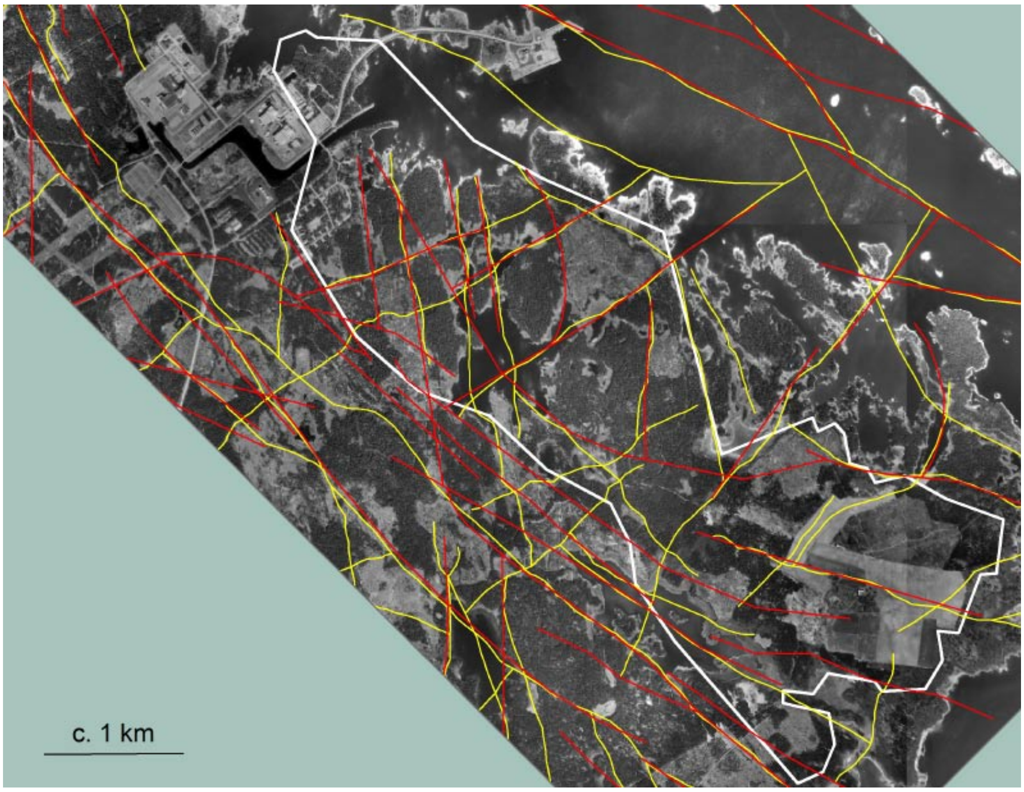

Figure 4-11. *Linked lineaments, uncertainty less than 2.0, superimposed on a mosaic of grey scale orthophotos. The primary (GeoVista) interpretation in yellow and the alternative (GTK) interpretation in red.*

The precision reported by GTK for magnetic lineaments ranges from 10 to 190 m, for topographic lineaments from 10 to 90 m and for EM lineaments from 10 to 125 m. However, most values are found at the lower end of the respective intervals. For linked lineaments, the reported precision is generally better than 50 m (60% of the lineaments) and often better than 25 m (20%). Eight per cent of the lineaments have been assigned a precision not better than 100 m and the precision of 6 lineaments is reported to be above 200 m.

It also seems that when assigning the precision to the linked lineaments, the displacement of the method specific lineaments, which are regarded to represent the same lineament, has been accounted for by GTK. The latter would explain the wider range of precision for some linked lineaments as compared to the method specific ones.

4.6 Concluding remarks

When the two sets of inferred lineaments are compared, it must be remembered that the two groups of geoscientists have performed the interpretation work under different conditions. GeoVista AB has been working in the area for a substantial period of time and has a profound knowledge of the geological setting. They have also completed fieldwork at the site. GTK does not possess that profound knowledge and has been presented the topographic and geophysical data along with some basic geological information only for the present project. The different conditions might very well have affected some expert judgements involved in the interpretation process.

The criterion uncertainty refers theoretically to the degree of clarity of the lineament but from time to time both groups seem to have considered also the probability of whether the lineament represents a deformation zone. Again, a different degree of insight in the local geology might have led to different expert judgements.

The length of a lineament, which is of considerable importance to the site description, is difficult to define and there are no objective criteria to tell when two lineaments should be kept separate or linked to form one single lineament. The linking is also scale dependent; lineament linked in large-scale models will frequently be divided into a number of shorter lineaments when studied in more detailed models.

The assigned precision of the lineaments differ more than expected, mostly due to different approaches to the assignment of precision to the method specific lineaments. In addition to this, the approach to the coordination process differs regarding the assigned precision to a lineament that has been derived from two somewhat displaced method specific lineaments.

In spite of the comments above, the general conclusions are that:

- The alternative interpretation does not, in general, show any major discrepancies as compared to the primary interpretation. The relatively few exceptions must however be seriously taken into consideration.
- The assigned lineament attributes offer the possibility to display the characteristics of each lineament or segment of a lineament very effectively. This facilitates the assessment of the lineaments, even though the attributes themselves cannot be used as simple assessment tools.

5 Lineaments and deformation zones

5.1 Lineament map

The lineament map forms, together with other information, the basis for further modelling of e.g. ductile or brittle deformation zones and dykes. This structural information is important to the site description of the 3D bedrock geology and will for example also be used as input to hydrogeological modelling and guide the layout of the repository. The overall site description will finally be subject to a safety assessment which will tell whether the site, from the safety point of view, is suitable for the location of a deep repository or not. The assessment of the lineament map and the further interpretation of lineaments as deformation zones, and the classification of these as probable, possible, major, local major etc zones is therefore essential to the site investigation and must be made accurately, should the site description be reliable.

As a consequence of the conclusions presented in the previous chapter, the primary lineament interpretation should form the basis for further evaluation. The alternative interpretation, covering the central, most important portion of the site investigation area must however be taken into consideration and the discrepancies between the two carefully assessed.

By merging and refining the two interpretation results, an updated lineament map can be established. This map may certainly be looked upon as a map of possible deformation zones, especially as long as no or very limited additional information is at hand. However, the extensive site investigation programme provides a considerable amount of information, e.g. from trenching, drilling and ground geophysics that can be used to further evaluate the lineaments. In many cases, the investigations have actually been focused on the lineaments.

In the following section, a strategy for assessment of interpreted lineaments is presented. The strategy includes additional investigations since the assessment of strategic lineaments in key areas must be supported by outcrop data or observations in trenches and/or drill holes. The aim of such investigations is that each lineament should be either verified as a deformation zone with appointed confidence (high, medium, low) or verified as not being related to a deformation zone. The strategy conforms well with the one presented by /Munier et al. 2003/.

5.2 Strategy for further assessment and investigations

The strategy presented here should be considered as guidelines not to be followed too rigorously. An approach of continuous and critical evaluation is strongly recommended. Apart from the modifications that may by be necessary, partial re-iteration of the process is likely needed.

5.2.1 Assumptions

The following general assumptions apply:

- The assessment should be based on the merged primary (GeoVista) and alternative (GTK) interpretations.
- All interpreted lineaments do exist (as lineaments).*
- All lineaments do not necessarily define deformation zones.
- There are no short cuts (single criterion or combination of criteria) that can be used as assessment tools but the assigned attributes can by used as a selection tool for further evaluation of the lineaments.
- It is in practice impossible to gain direct information on all lineaments, which implies that generalisations based on expert judgements have to be made.
- The major lineaments in key areas are critical for the site evaluation and must be investigated by trenching (if no outcrops are available) and possibly also by drilling.

*) The number of "erroneous lineaments" (drilling artefacts, misinterpreted anthropogenic features etc) is assumed to be insignificant.

5.2.2 Strategy

The proposed strategy applies to the investigation of a small area that forms the north-western part of the present local model area. The regional model area can, in principle, be treated in the same way but not in so much detail.

As the first step, a careful assessment of the inferred lineaments is made according to the following principles:

Lineaments longer than 3,000 m (Figure 5-1) are studied individually. The complete lineament interpretation process (method specific interpretation, coordination and linking of lineaments) should be reviewed. All data relevant for a geological interpretation of the lineaments are compiled. Assessment of lineaments that are crossing or delimiting the repository area (volume) under investigation must be based on direct information (outcrop data, trenching, drilling). When needed, recommendations for complementary investigations are given.

Lineament 1,000–3,000 m (Figure 5-2) are treated as above but assessment based on indirect information (mainly ground geophysics) can be accepted.

Lineaments 500–1,000 m (Figure 5-3) are studied in a more generalised manner. The assessment is mainly based on indirect information.

Lineaments shorter than 500 m (Figure 5-4) are generally not considered. In further modelling of the site, these lineaments will have to be treated statistically.

The second step includes the complementary investigations recommended during step 1.

The third step is the compilation of the results into a map of deformation zones of variable confidence. If applicable, other geological features such as dykes can also be included.

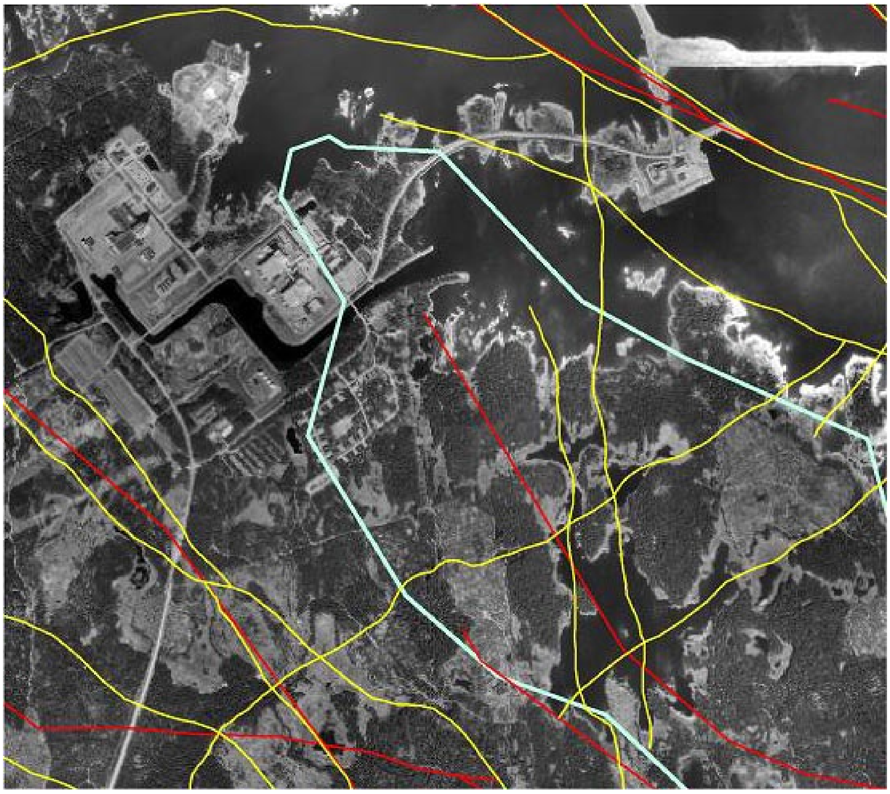

Figure 5-1. *Linked lineaments longer than 3,000 m superimposed on a mosaic of grey scale orthophotos. The primary (GeoVista) interpretation in yellow and the alternative (GTK) interpretation in red.*

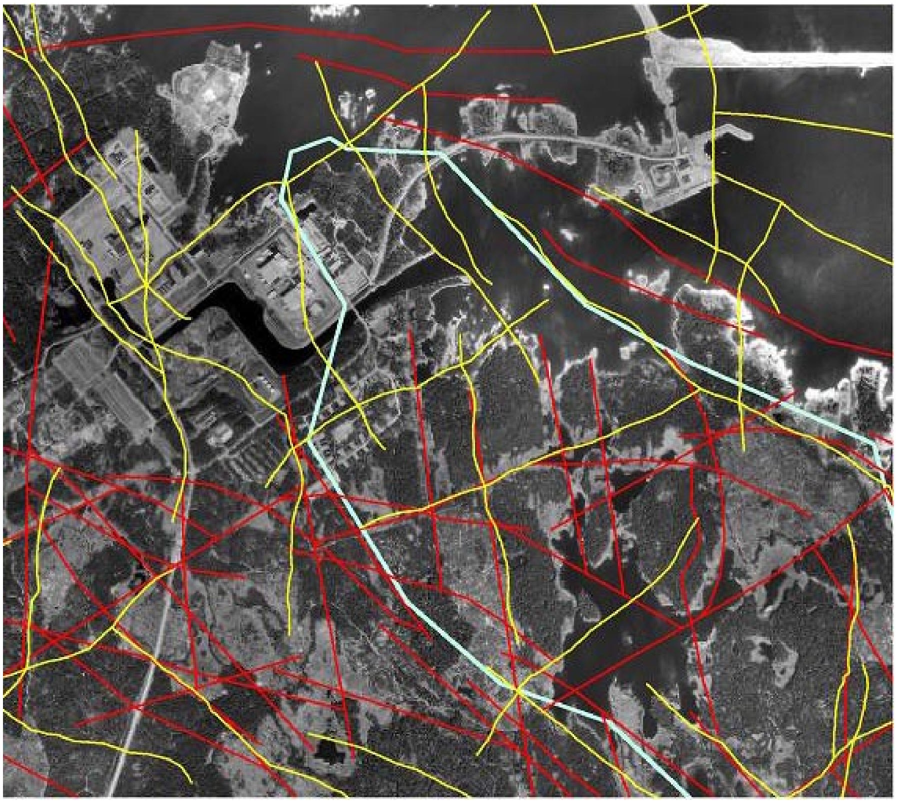

Figure 5-2. *Linked lineaments 1,000–3,000 m superimposed on a mosaic of grey scale orthophotos. The primary (GeoVista) interpretation in yellow and the alternative (GTK) interpretation in red.*

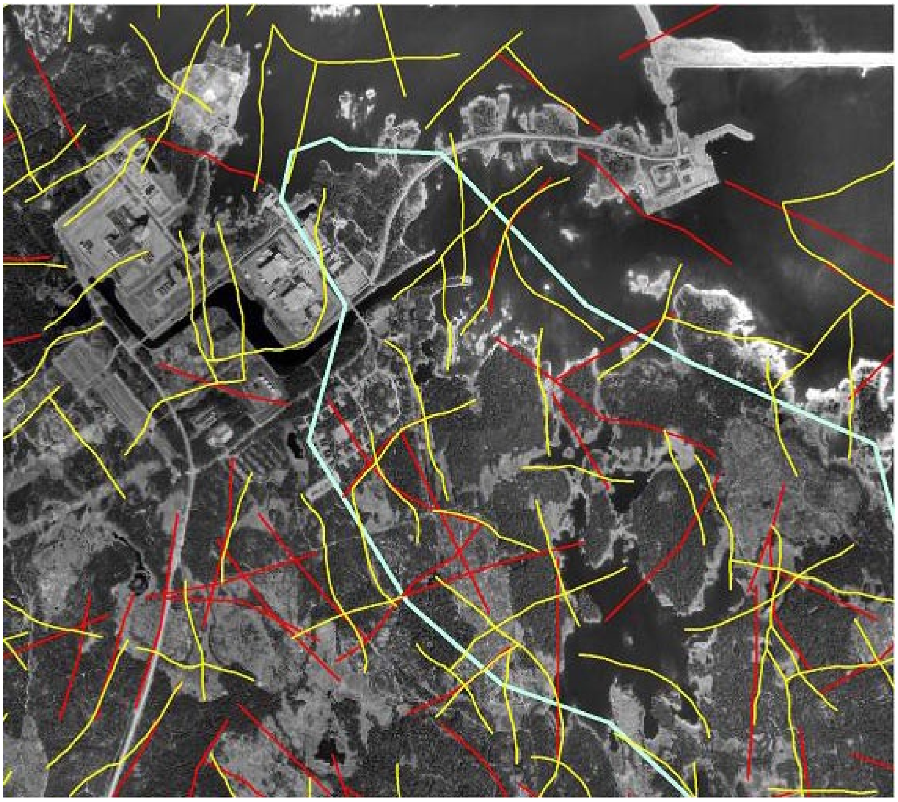

Figure 5-3. *Linked lineaments 500–1,000 m superimposed on a mosaic of grey scale orthophotos. The primary (GeoVista) interpretation in yellow and the alternative (GTK) interpretation in red.*

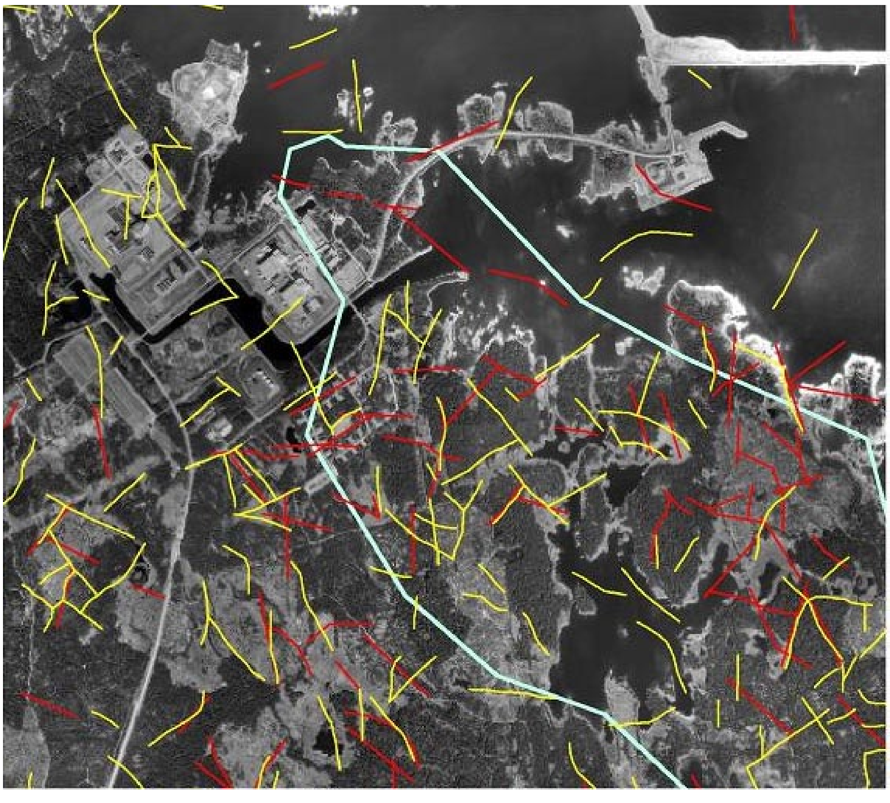

Figure 5-4. *Linked lineaments shorter than 500 m superimposed on a mosaic of grey scale orthophotos. The primary (GeoVista) interpretation in yellow and the alternative (GTK) interpretation in red.*

6 Conclusions

The comparison of two independent lineament interpretations has revealed that the results are, in principle, reproducible. However, there are discrepancies that are judged to be significant.

The attributes assigned to the inferred lineaments provide an excellent tool for displaying the characteristics of a particular lineament, which facilitates the further assessment of the results. However, the use of a single attribute or a combination of attributes as a stand-alone criterion for the assessment can be seriously misleading.

Whether a lineament represent a deformation zone or not must be concluded on the basis of all available data from outcrop observations, trenching, drilling, ground geophysics et cetera. The assessment should also include a revision of the whole interpretation process (method specific interpretation, coordination and linking of lineaments). When necessary, new such data must be acquired. This applies especially to the lineaments judged to be longer than 3,000 m but also for the majority of the lineaments that are between 1,000 and 3,000 m in length.

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