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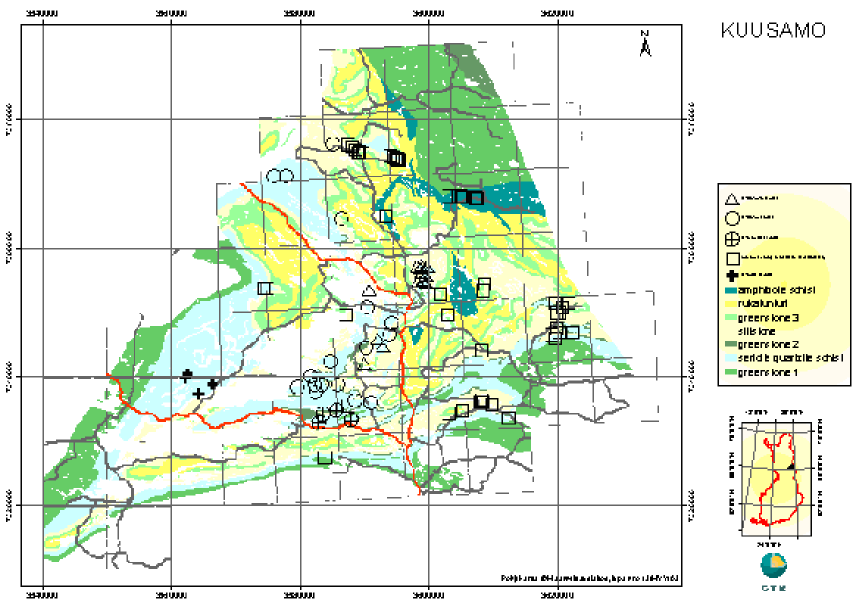
# *Conceptual Fuzzy Logic Prospectivity Analysis of the Kuusamo Area*

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Title of report

**Conceptual Fuzzy Logic Prospectivity Analysis of the Kuusamo Area**

Abstract

A prospectivity analysis was made of the Kuusamo area, Finland, in order to highlight subareas favourable for Fe-oxide Cu-Au-U (Olympic Dam type) deposits. Available geological, geochemical and geophysical data sets were integrated in GIS using a fuzzy logic overlay method. The total study area was 4789 $km^2$, which covers the Kuusamo Greenstone Belt. Special emphasis was given to Sericite Quartzite Formation, Siltstone Formation and Greenstone Formation II. A group of 11 target areas could be delineated for possible further studies.
Detailed structural interpretation would give valuable additional information for this analysis; however, such study is not available in the Kuusamo area.
The background geology and ore geology relevant to this work are based on the latest interpretations, presented in Vanhanen (2001).
None of the result targets were excluded because of possible restrictions due to existing rights based on Mining Law or restrictions due to environmentally protected areas.
This report is accompanied with a CD-ROM disk, comprising the report in MS Word 2000 format.

Keywords
Uranium deposits, prospectivity analysis

Geographical area
Kuusamo, Finland

Map sheet

Other information
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Raportin nimi

**Conceptual Fuzzy Logic Prospectivity Analysis of the Kuusamo Area**


Tiivistelmä

Kuusamon alueelta tehtiin prospektiivisuusanalyysi, jonka tarkoituksena oli erotella alueelta suotuisia kohteita rautaoksidi-kulta-kupari-uraani (Olympic Dam) –tyyppisten esiintymien etsintään. Työhön käytettiin saatavilla olevia geologisia, geokemiallisia ja geofysikaalisia tietoja, joita yhdisteltiin paikkatieto-ohjelmalla sumeaan logiikkaan perustuvilla menetelmillä. Tutkitun alueen kokonaisala on 4789 $km^2$, mikä kattaa Kuusamon vihreäkivivyöhykkeen. Erityisesti painotettiin serisiittikvartsiittimuodostumaa, silttikivimuodostumaa ja vihreäkivimuodostumaa II. Kaikkiaan pystyttiin osoittamaan 11 eri kohdealuetta, joille jatkotutkimuksia voitaisiin suunnata. Analyysia vahvistaisi yksityiskohtainen rakennegeologinen tulkinta, mutta sellaista ei ole alueelta saatavissa.
Työssä käytetty geologinen ja malmigeologinen taustatieto perustuu viimeisimpiin tulkintoihin (Vanhanen 2001).
Työstä ei suljettu pois kohteita mahdollisten kaivoslain mukaisten rajoitusten tai luonnonsuojeluun perustuvien rajoitusten vuoksi.
Tilaajalle on toimitettu raportin lisäksi CD-ROM -levyke, joka sisältää raportin MS Word 2000 –muodossa.



Asiasanat (kohde, menetelmät jne.)
Uraaniesiintymät, prospektiivisuusanalyysi


Maantieteellinen alue (maa, lääni, kunta, kylä, esiintymä)
Kuusamo, Suomi

Karttalehdet

Muut tiedot
Raportin englanninkieltä ei ole tarkastettu

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## *Contents*

## Introduction

The aim of this project is to make a prospectivity analysis of the Kuusamo area in order to highlight subareas favourable for Fe-oxide Cu-Au-U (Olympic Dam type) deposits. This will be done by integrating available geological, geochemical and geophysical data sets in GIS using a fuzzy logic overlay method. The total study area is 4789 $km^2$, which covers the Kuusamo Greenstone Belt. Special emphasis is given to Sericite Quartzite Formation, Siltstone Formation and Greenstone Formation II.

Detailed structural interpretation would give valuable additional information for this analysis; however, such study is not available in the Kuusamo area. In a more general scale, geophysics and the major structures of the area have been interpreted in many papers of Silvennoinen (1992) and in Airo (1999). The radiometric data of the Kuusamo area have previously been studied by Arkimaa (1997).

The background geology and relevant ore geology of this work are based on the latest interpretations, presented in Vanhanen (2001).

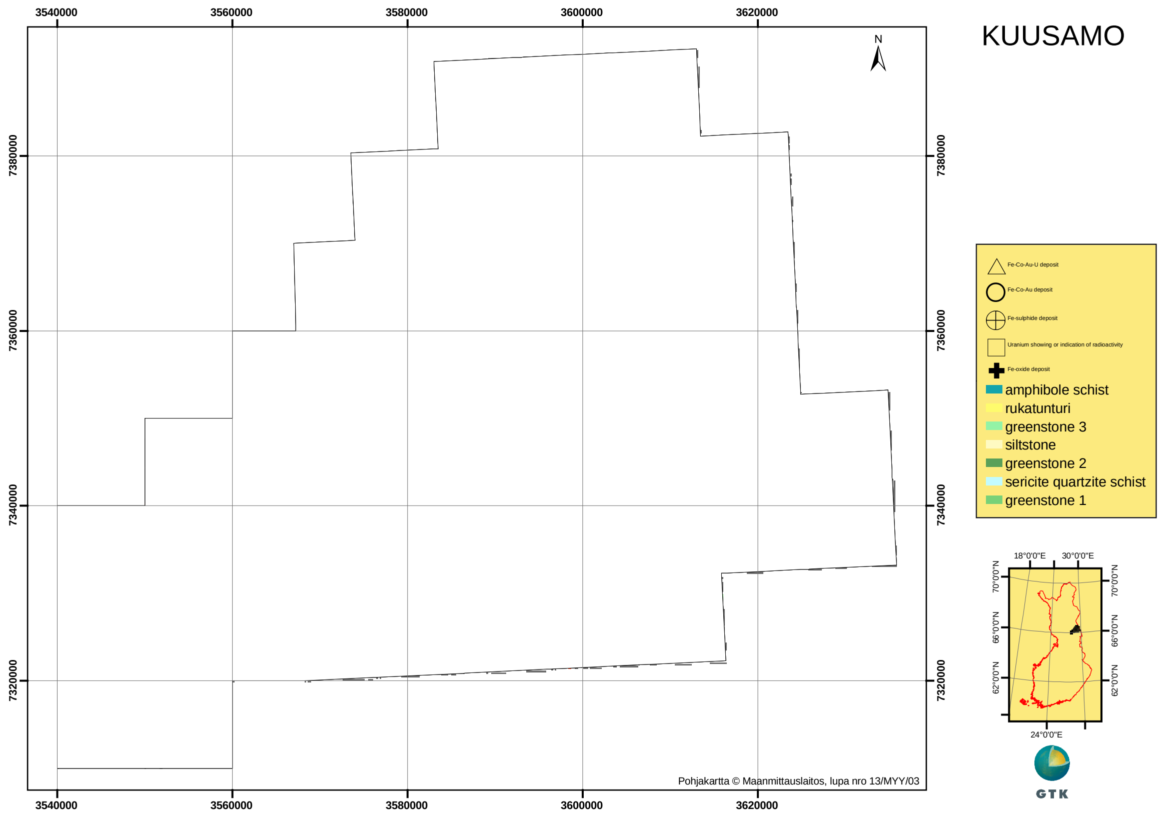


*Figure 1. Location of the area of interest and geological formations. Location of the known mineral occurrences are from Vanhanen (2001).*

## *Methodology*

Quantitative geography and spatial analysis consist of several branches giving tools for statistical and geostatistical operations to be used to conduct mineral prospectivity mapping. These methods can be divided into two main categories, based on the approach: (I) empirical (data driven) and (II) conceptual (knowledge driven) methods (Bonham-Carter, 1994). In the empirical approach the known mineral deposits are used as 'training points' for examining spatial relationships between the known deposits and particular geological, geochemical and geophysical features. The identified relationships between the input data and the training points are quantified and used to establish the importance of each evidence map and finally integrated into a single mineral prospectivity map. The examples of the empirical methods used are weights of evidence, logistic regression and neural networks. The other major branch is the conceptual (knowledge driven) approach, where we use re-formulation of knowledge about deposit formation into mappable criteria (i.e. threshold values in geochemistry and geophysics etc., certain structures or formations in the geological maps). The areas that fulfil the majority of these criteria are highlighted as being the most prospective. These methods are dependent on the geologist's input and exploration models, being thus fairly subjective in nature. On the other hand by selecting a conceptual method one can benefit from the expertise of the geologists during the modelling process. The methods belonging into this branch include Boolean logic, index overlay (binary or multi-class maps) and fuzzy logic. Especially the latter has been recently widely implemented for the data integration and mineral prospectivity mapping purposes (Chung and Moon, 1990; An et al., 1991, D'Ercole et al., 2000; Knox-Robinson, 2000). For this project we selected the empirical fuzzy logic overlay as a modelling tool due to the lack of appropriate training sites required for empirical modelling. There are a few known Au occurrences in Kuusamo area, but they represent variable types of deposits and cannot therefore be used as a training set.

Figure 2 illustrates the modelling methodology as a flow chart. Modelling is iterative in a sense that after creating initial models one can improve the models by modifying the parameters and selecting the input data sets and then create new models.

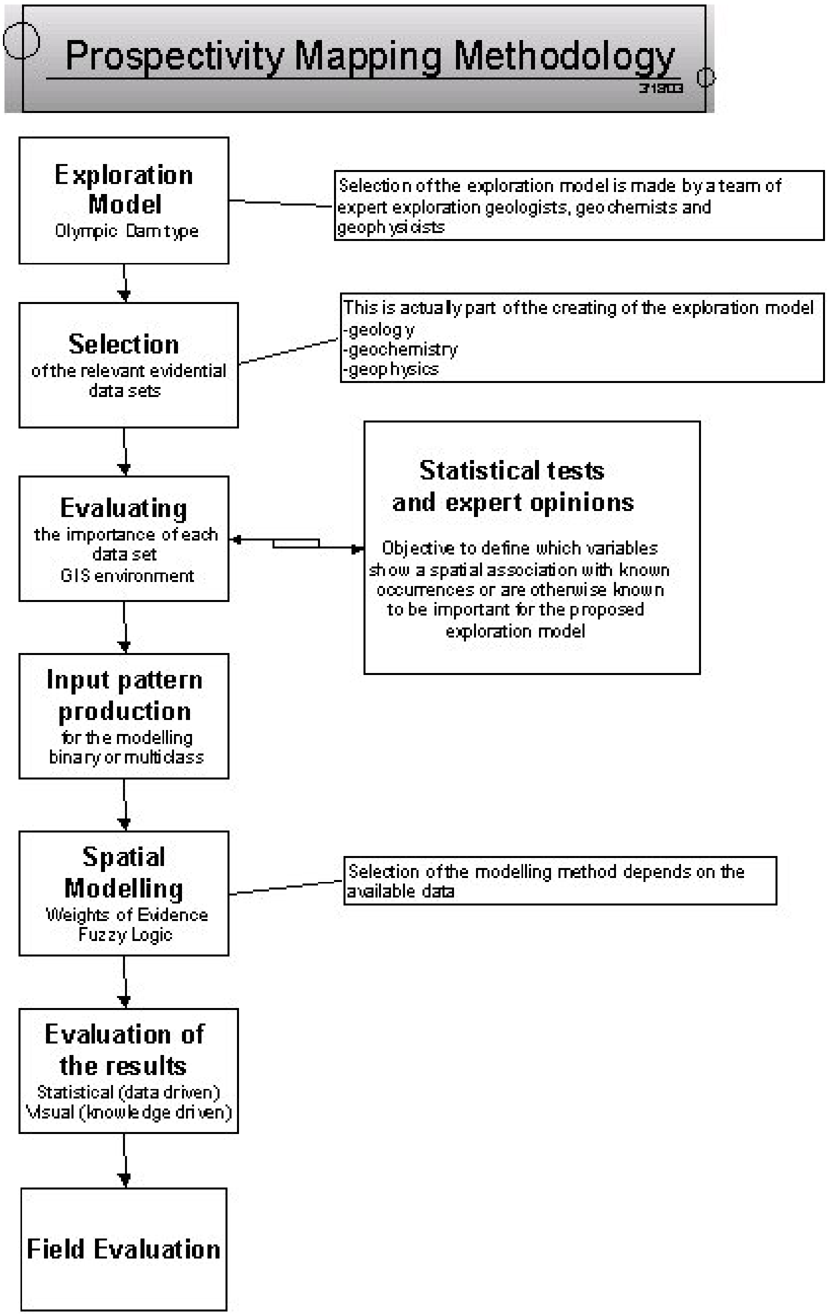


*Figure 2. Modelling methodology*

The conceptual approach uses the expertise of the exploration geologists, geochemists and geophysicist to define the threshold values for the evidential data sets. For this study the fuzzy logic spatial modelling was also produced by using ArcSDM software (Kemp et al., 2001). In classical set theory, the membership of a set is defined as true or false (1 or 0) whereas membership of a fuzzy set is expressed on a continuous scale from 1 to 0 (e.g. 'anomalous' vs. 'not anomalous'). The values of fuzzy membership can be chosen based on subjective judgment of an expert. In this study the fuzzy membership function for each evidential element was defined by experts by taking in account the statistics of each element and the geological background values within each area of interest. Membership reflects degree of truth of some proposition or hypothesis, which is often a linguistic statement. To define the membership function one needs to define the thresholds for 'not anomalous' and 'anomalous' values and then a function describing the 'maybe – probably' values in between these two thresholds. In this work a linear function between the thresholds was assumed to be appropriate, but the shape of the actual function varies due to classification prior giving fuzzy membership values for the classes of the maps. The fuzzy membership values reflect the relative importance of the each class of the maps used. The closer the fuzzy membership value is to 1 the more significant is the anomaly. The hypothesis used was 'is there a gold deposit' and the fuzzy sub sets or intermediate hypotheses were like 'data showing an alteration zone' and 'data showing signs of sulphides'.

After giving the fuzzy membership functions for each evidential map relevant to the current exploration model a variety of operators can be used to combine the membership values together. In this paper we have used the following operators (Bonham-Carter, 1994):

**Fuzzy AND**: This is equivalent to Boolean AND operation (*logical intersection,* $C = A \cap B$) and could also be called as Min-operator as it results an output, which is controlled by the smallest fuzzy membership values at each location. It results in a conservative estimate of set membership, with tendency to produce small values and minimum areas. Useful to find the areas where all the evidence used need to be present together for the hypothesis to be true.

$$\mu_C(x) = MIN(\mu_A(x), \mu_B(x), \mu_B(x), ...) \quad (1)$$

where $\mu_A$ is the membership value for map A, $\mu_B$ for map B etc.

**Fuzzy OR**: This is equivalent to Boolean OR (logical union, $D = A \cup B$) operator and can be called as Max-operator as it results an output. The output membership values are controlled by the maximum values of any of the input maps. By using this operator any positive evidence may be sufficient to suggest favourability.

$$\mu_{combination} = MAX(\mu_A, \mu_B, \mu_B, ...) \quad (2)$$

When using fuzzy AND or fuzzy OR, a fuzzy membership of a single piece of evidence controls the output value.

**Fuzzy Algebraic Product**: The combined fuzzy membership values tend to be very small due to the effect of multiplying several numbers less than 1. The output is always smaller than, or equal to, the smallest contributing membership value. All the contributing values have some effect on the result.

$$\mu_{combination} = \prod_{i-1}^{n} \mu_i \quad (3)$$

**Fuzzy Algebraic Sum**: The result is always larger (or equal to) the largest contributing membership value.

$$\mu_{combination} = 1 - \prod_{i-1}^{n} (1 - \mu_i) \quad (4)$$

**Fuzzy Gamma Operation**: This is defined in terms of the fuzzy algebraic product and the fuzzy algebraic sum, being a combination of these two operations.

$$\mu_{combination} = (\text{Fuzzy algebraic sum})^{\gamma} * (\text{Fuzzy algebraic product})^{1-\gamma} \quad (5)$$

where parameter $\gamma$ is given in the range from 0 to 1.

## *Exploration model*

The aim is to make a prospectivity analysis to highlight favorable areas for Olympic Dam type deposits within Kuusamo area, Northern Finland. The input data selected includes high-resolution airborne geophysics, regional till geochemistry and digital bedrock geological data (same as printed map in scale 1:200000 in Vanhanen, 2001). The proposed symptoms of the desired deposit type in the evidential data sets were following:

1. Indication of possible sulphides in till geochemistry (i.e. anomalous Fe, Cu and Co occurring all together). -> **Fuzzy AND4 Till**
2. Anomalous P, Y and La in till geochemistry indicating minerals in alkaline rocks. -> **Fuzzy AND1 Till**
3. Anomalous Ba, K and P in till geochemistry indicating alteration zones. -> **Fuzzy AND3 Till**
4. Anomalous Y and Ti in till geochemistry indicating possible brannerite or davidite sources. -> **Fuzzy AND2 Till**
5. Anomalous Te in till geochemistry as a pathfinder element for Au.
6. Airborne uranium radiation anomalies.
7. High-magnetic electromagnetic real anomalies. **-> Fuzzy AND Geophys**
8. Certain geological formations were classified as important (i.e. Sericite Quartzite Formation, Siltstone Formation and Greenstone II) and others less important.

**Fuzzy AND** operator was selected to make a conservative estimate of the anomalous areas in the regional till geochemistry. Te replaced Au in the final model since the analytical quality of Te was so much better.

The current exploration model gives an estimate on Fe-oxide Cu-Au-U favorability in Kuusamo area in general. The regional modelling was done in an area of 4789 $km^2$ (Figure 1).

The flow charts of the used model are shown in Figures 3 and 4. The integration process was done in several steps and also the intermediate results are shown.

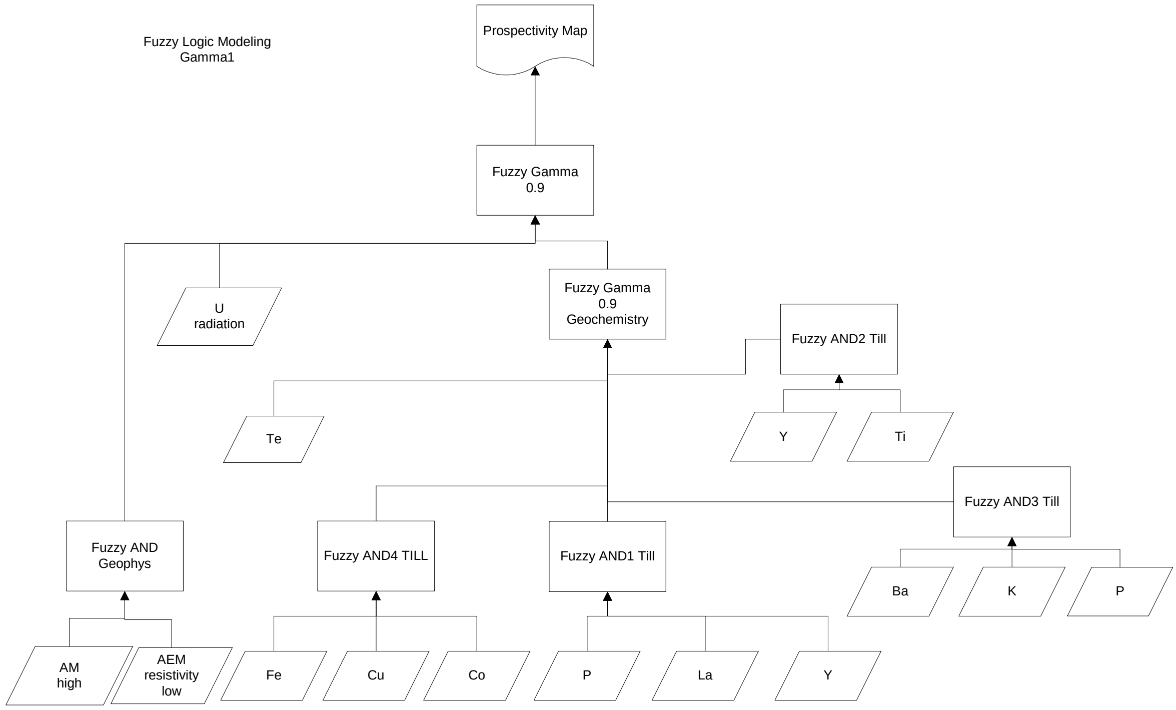


*Figure 3. The flow chart for the model 'Gamma1' used in this study. This model includes only the geochemical and the geophysical evidence.*

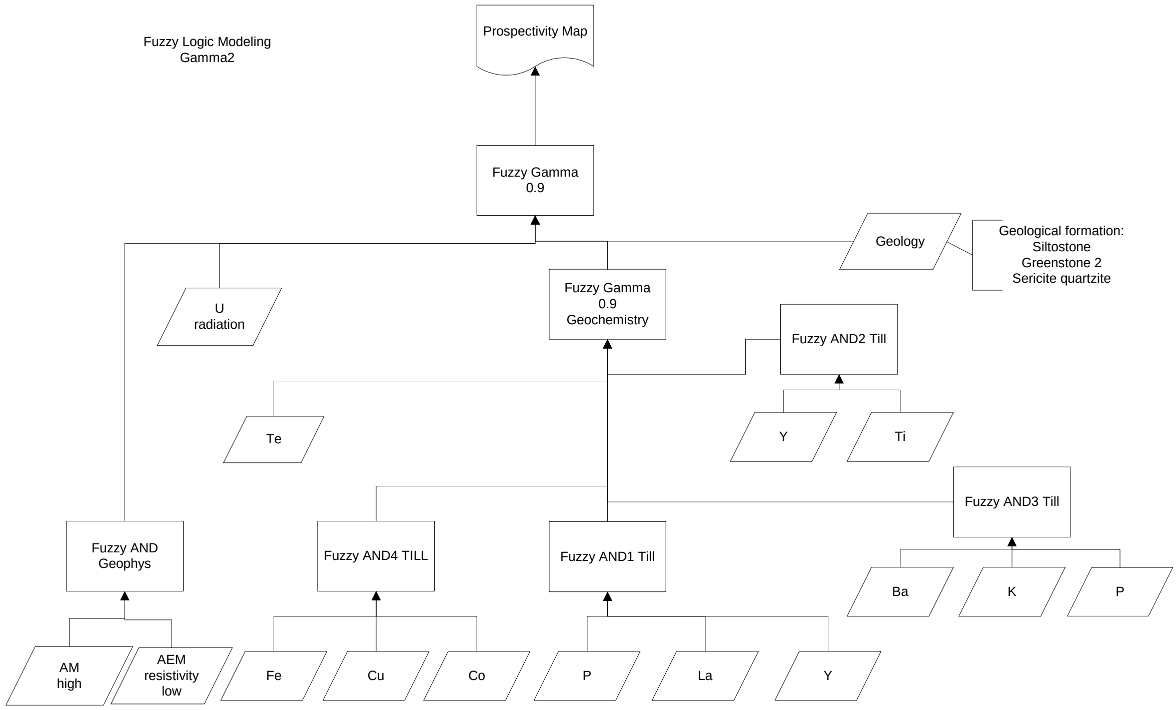


*Figure 4. The flow chart for the model 'Gamma2' used in this study. This model includes also the geological evidence in addition to geochemistry and geophysics.*

## *Airborne geophysics*

The study area has been covered by high-resolution systematic low altitude airborne geophysics by GTK. The data is composed of 10 separate surveys (Figure 5; Table 1). The oldest flights date from 1980 and the most recent flight was completed in 2000. The mapped parameters are magnetic total field intensity, two electromagnetic field components and four gamma radiation components (multichannel total count and K, U & Th channels). The flight altitude was about 30 to 40 meters and line spacing 200 meters. The profile direction has been either N-S or E-W according to the dominant strike of the bedrock geology. As the flying speed is around 180 km/h, and the recordings have been done 2 to 10 times per second in magnetic and 2 or 4 times per second in electromagnetic measurements, the data point separation depending on method is 5 to 25 meters. The resolution of grids interpolated from data is 50 m x 50 m.

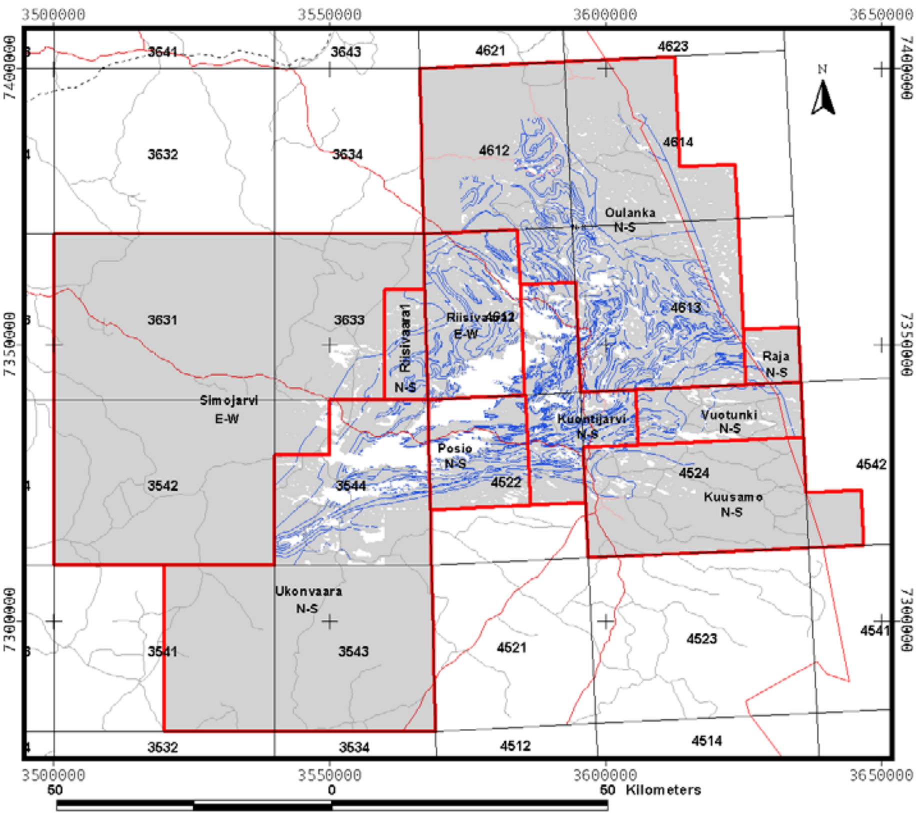


*Figure 5. Airborne surveys in the Kuusamo area. Flight direction is indicated within each area.*

| Flight Area | Flight Direction | Year |
|---|---|---|
| Posio | N-S | 1980 |
| Kuontijarvi | N-S | 1982 |
| Oulanka | N-S | 1984 |
| Vuotunki | N-S | 1986 |
| Kuusamo | N-S | 1987 |
| Simojarvi | E-W | 1989 |
| Riisivaara1 | N-S | 1991 |
| Raja | N-S | 1996 |
| Ukonvaara | N-S | 1998 |
| Riisivaara2 | E-W | 2000 |

*Table 1. Summary of the airborne surveys in the Kuusamo area.*

***Regional till geochemistry***

Sampling density is one sample per 4 km$^2$ (Figure 6) and sampling was conducted in the 1980s (Salminen, 1995). The samples were collected as a composite of 3-5 sub-samples taken by a portable percussion drill equipped with a through flow bit from the average depth of 1.5 meters. The sampled material was chemically unaltered parent till. From dried samples the <0.06 mm fraction was sieved for analysis. From hot aqua regia assay abundances of Al, Ba, Ca, Co, Cr, Cu, Fe, K, La, Li, Mg, Mn, Mo, Ni, P, Pb, Sc, Sr, Th, Ti, V, Y, Zn and Zr were determined by ICP-AES. In addition Au, Te and Pd determinations were carried out by AAS.

The original point data was interpolated to grid size of 200 m by 200 m using a simple inverse distance weighting method (IDW), with 12 nearest neighbours. The exponent of distance used in the calculation is given by a power parameter, which controls the significance of surrounding points on the value given to the cell being analyzed. A higher power results in less influence from distant points. In this case we used power of two.

Unfortunately the quality of assays for some of the interesting elements was not good enough and the values were either below detection limit or on the limit. These cases were Mo, Pb, Th and Au. Te was used instead of Au since it proved to be of better quality and usually correlates well with Au.

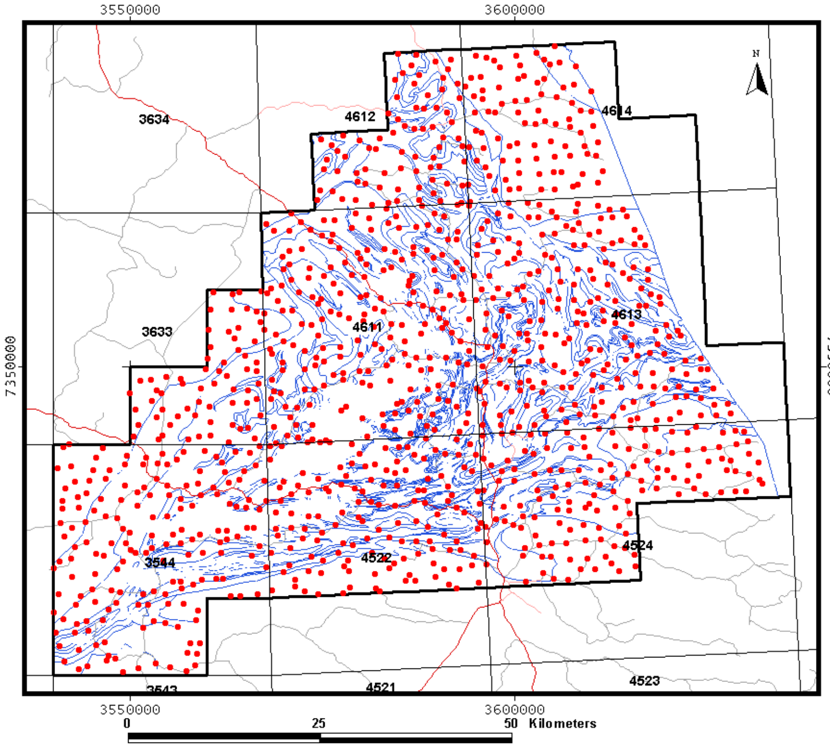


*Figure 6. Location of the original sampling points of the regional till geochemical survey in the Kuusamo area.*

Following combinations of till geochemistry were used:

1. La, Y and P: possible sources monazite, xenotime
2. Fe, Cu and Co: sulphides
3. Y and Ti: possible sources brannerite, davidite
4. P, K and Ba: alteration zones

Anomalous concentrations of these elements in till can be due to other sources too, but having them combined as in this study somewhat reduces the amount of sources. On the basis of experience in exploration in this area, Erkki Vanhanen suggested using Te instead of Au. Te proved to be more reliable and better quality than Au.

*Table 2. Thresholds for Fuzzy membership values for the evidential data sets.*

| Evidential data set | Not anomalous (0) | Anomalous (1) |
|---|---|---|
| Airborne magnetic data (nT) | <-1700 | >1400 |
| Airborne EM (ppm) | <2000 | <20 |
| Airborne radiation: uranium channel (eUppm) | <0 | >70 |
| Y in till (ppm) | <4.8 | >11.6 |
| Ti in till (ppm) | <760 | >1640 |
| P in till (ppm) | <349 | >761 |
| K in till (ppm) | <1073 | >3856 |
| La in till (ppm) | <8.7 | >27.6 |
| Ba in till (ppm) | <27.6 | >79.1 |
| Te in till (ppb) | <4.1 | >14.8 |
| Cu in till (ppm) | <29 | >89 |
| Fe in till (ppm) | <11290 | >27000 |
| Co in till (ppm) | <3.4 | >17.2 |

## *Data integration*

The intermediate results of modelling are shown in Figures 7-11 and as two final prospectivity maps, Gamma1 and Gamma2, in Figures 12 and 13. The difference between these two models is that geology was left out from Gamma1 (Figure 12). The intermediate results, i.e. combined geochemistry and geophysical maps, are useful in evaluation of the influence of the original data on the final model. Combined geophysics (Figure 9) was given only a moderate weight since the quality of electromagnetic survey varies quite a lot.

The available evidential data sets were combined in several steps to produce the final prospectivity maps. Especially geochemical evidence was used to predict several phenomena and intermediate modelling results were done. The data integration was accomplished as was described earlier in the chapter 'Exploration model'. The intermediate results of integrating till geochemistry are shown in Figure 7. The resulting combination was achieved finally using **fuzzy gamma operator** (Figure 8), while for the earlier combinations **fuzzy and operator** was used. Till geochemistry shows certain interesting anomalous areas, which can, however, be partly due to black schists.

Geological map was also classified into favourable and less favourable areas. This classification is highly subjective and relies on the interpretation of the geological mapping and airborne geophysical surveys. In the first model (Gamma1) this interpretation was not used and the result relies entirely on geophysical and geochemical evidence.

The final results (Figure 14) point out several target areas, which need further estimation. In addition there are several smaller areas with significant responses, but which are due to only one sample and cannot be considered very reliable.

The main target areas are:

| | |
|---|---|
| Noukajärvi | Hukkavaara |
| Kätkytvaara-Maaninka-vaara | Katajasuo |
| Liikasenvaara | Syrjäsuo |
| Juuma | Hyväniemi |
| Särkijärvi-Paljakka | Ruka |
| | Oulanka |

## *General geology of the main targets*

The **Noukajärvi** prospectivity area consists of garnet and amphibole-bearing micaceous rocks, quartzites (Sericite Quartzite Formation (SQF)), greenstones (Greenstone Formation II (GF II) and III (GF III)) and granitic rocks with minor alkalic affinity. The rocks are metamorphosed mostly within the amphibolite facies. Structurally the area seems to be an intersection of ductile SW-NE and SE-NW oriented fault zones, which are at least partly recovered. The radioactivity of the granitic rocks in the area is anomalously high even for granites. Two uranium showings were located in the 1970s at Simonkorpi in the eastern end of the area. One of them is situated in alaskitic neosomes of migmatitic rocks, and the other is hosted by granitic syenites with alkalic character. In addition of native gold the latter contains also copper minerals varying from native copper to chalcopyrite. Furthermore, intensive magnetite disseminations in quartzitic rocks are located close to these showings as well as some local anomalously uranium-bearing glacial quartzite erratics of unknown origin.

The **Kätkytvaara-Maaninkavaara** prospectivity areas are situated in the northwestern part of the Hyväniemi-Maaninkavaara anticline. The rocks range from SQF up to the GF III along with numerous mafic dykes. The metamorphic degree of the rocks increases from greenschist facies up to amphibolite facies toward NW. Except for radiometric ground survey and boulder tracing, targeted drilling and trenching in the 1970s and 1980s, the area is not well explored. However, four Co, Cu and Au-bearing sulphide deposits along with minor sulphide showings and boulders were found in the area.

In the **Liikasenvaara** prospectivity area the uppermost Amphibole Schist Formation (ASF) and the lowermost Greenstone Formation I (GF I) are situated side by side, and the area is specific in till geochemistry compared to the other areas in the Kuusamo area. Reason for that is not fully understood. The strongest prospectivity area seems to hit the contact between the Rukatunturi Quartzite Formation (RQF) and ASF. This zone has been found to contain hydrothermal uranium and copper with albitisation in the other parts of the Kuusamo area. Nevertheless, except for very general uranium exploration and carbonate rock studies in the 1950s, 1960s and 1970s the Liikasenvaara area is poorly studied. As a result of the uranium exploration small uranium showings were located in mica schist. The showings were not studied in detail.

The **Juuma** prospectivity area is very interesting, because several uranium occurrences were recognized in the area and till geochemistry indicates Fe, Co and Cu anomalies in till. The rocks of the area, forming a N-S oriented syncline, belong to the succession from the Siltstone Formation (SF) to the uppermost

ASF. The latter is the only formation containing black schists in Kuusamo. Consequently, the till anomalies can be partly due to black schists, but on the other hand the black schists are not always anomalous for these metals, and the anomalous area is set transversely to the strikes of the black schists, extending also outside of the black schists. Furthermore, detailed geochemical studies of the black schist have not been done in the Kuusamo area.

The uranium showings, including variable amounts of Au and Co- and Cu-minerals, are associated with albite-carbonate veins, which are hosted by the GF III and differentiated mafic dolerite dykes and sills. Albitisation of the area is multi-phase and in places very intensive, most of it preceding the albite-carbonate veins. Thus the hydrothermal alteration has taken place in several stages enabling the existence of dormant mineral deposits.

Radioactive survey and boulder tracing have been done in the **Särkivaara-Paljakka** prospectivity area in the 1950s, 1960s and 1980s, and several indications of radioactivity were found (boulders, radioactive wells and peat anomalies). Some parts of the rocks belonging to SQF are anomalously radioactive (twice the common background). Also hydrothermal alteration including albitisation was recognized in the area. Hydrothermal activity is usually connected with tectonic structures. Major indications of sulphide or iron minerals were not found. In general the rocks of the area belong mainly to SQF, GF II and SF, which were intruded by mafic dolerite dykes and sills.

The **Hukkavaara** prospectivity area includes the rocks of the lowermost stratigraphic units up to SF. Except for prospectional radiometric ground survey the area is poorly studied. Indications of radioactivity were still noticed. In addition to peat anomalies and some boulders, anomalous radioactivity was found in fine-grained parts as well as in conglomeratic parts of the sericite quartzites. Furthermore, bottom sediments rich in uranium were located in the fault-controlled lake Kivi-Piskamojärvi. However, signs of major uranium deposits or iron and copper deposits were not located but these were not prospected either.

The prospectivity area of **Katajasuo** consists of the rocks of SQF. Except for some albite-carbonate veins similar to Juuma area, signs of mineralization were not detected in the area. However, the area is not well explored.

The prospectivity area of **Syrjäsuo** is located at the contact zone between SQF and SF. In this area the contact zone is usually quite continuously occupied by GF II. Four barren sulphide deposits were found a little bit outside of the prospectivity area, in which the ore-forming mineralization is not known. However, the area is poorly exposed and therefore not well known. South of the most prospective area small uranium showing of Kouvervaara type was located.

GTK has done geophysical ground measurements and till geochemistry in the **Hyväniemi** area, which is situated in SQF. However, only one small sulphide showing was located in the western part of the prospectivity area, but hydrothermally altered rocks were detected in the western end of the cape Hyväniemi and an almost massive magnetite bed (50 cm) was detected in drill cores east of the prospectivity area.

The **Ruka** area is covered by thick till overburden. Therefore the bedrock geology is not well known. However, reconnaissance radiometric ground measurements indicated anomalous radioactivity of the till cover in a wide area. Furthermore, a few red uranium-bearing albite-rock boulders were located in the radioactive area.

The prospectivity area at **Oulanka** belongs to SQF. South and southwest of the area several uranium showings similar to the Juuma area were found, but signs of sulphide or iron oxide rocks have not been reported.

## *Restrictions to land use and exploration*

### *Mining Law*

The restrictions to exploration due to existing mining concessions, claims and reservations of claim can be found on the home pages of the Ministry of Trade and Industry in the Internet, at http://www.vn.fi/ktm/4/4_mien.htm in MapInfo format. The Active Map Explorer of GTK (at http://maps.gsf.fi/gtk/eexpert.asp) also contains information of these areas. Because of limited rights to these data, comparison of prospectivity target areas and areas of existing mining rights have not been included in to this work.

### *Environmental protection*

The protection areas in the Kuusamo area (under the environmental administration) can be found in the Internet presently only in Finnish, e.g. at http://www.vyh.fi/luosuo/n2000/ppo/kuusamo.htm. Because of the same reason as above, comparison of prospectivity target areas and protection areas has not been included into this work.

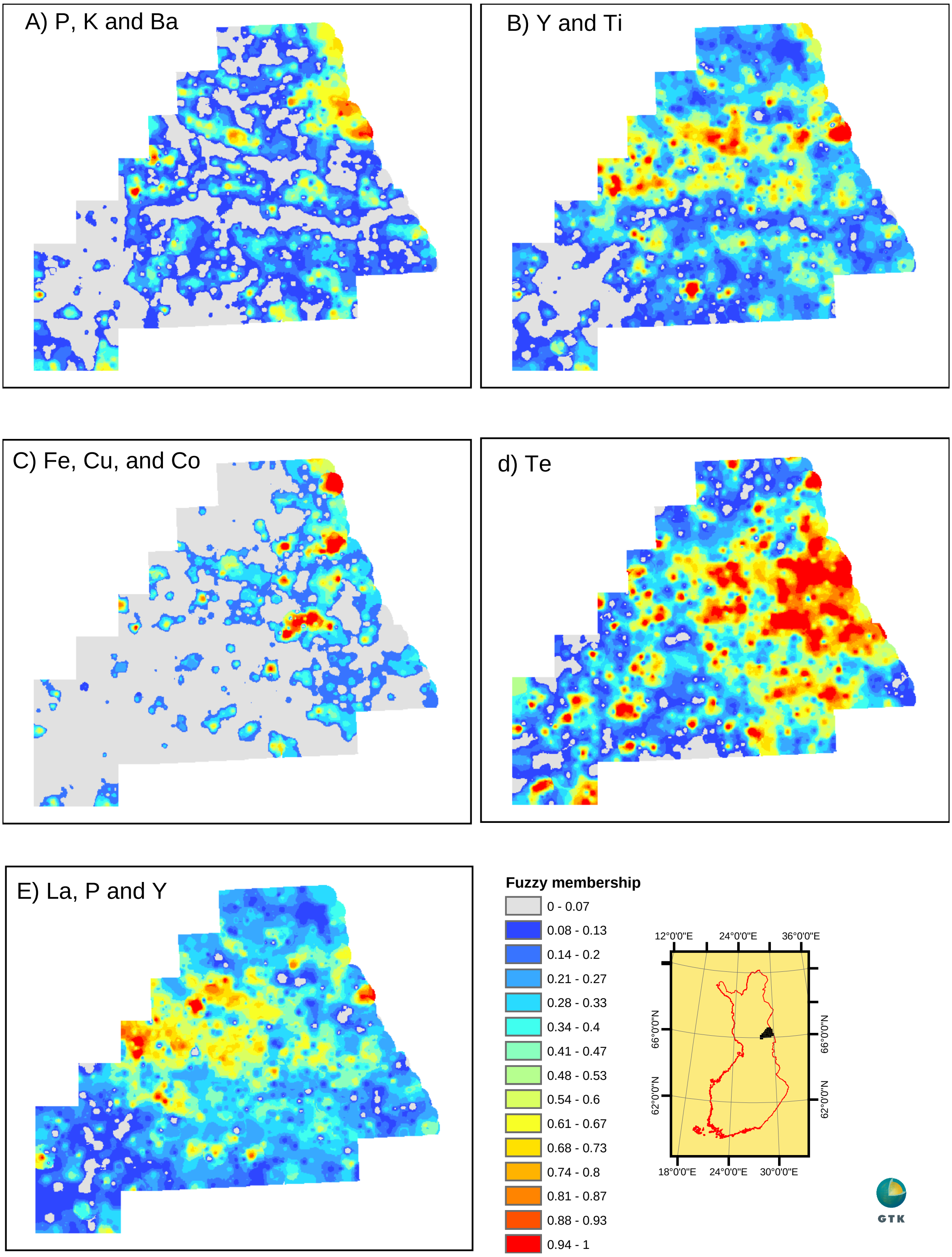


*Figure 7. Fuzzy membership values for the geochemical evidence.*

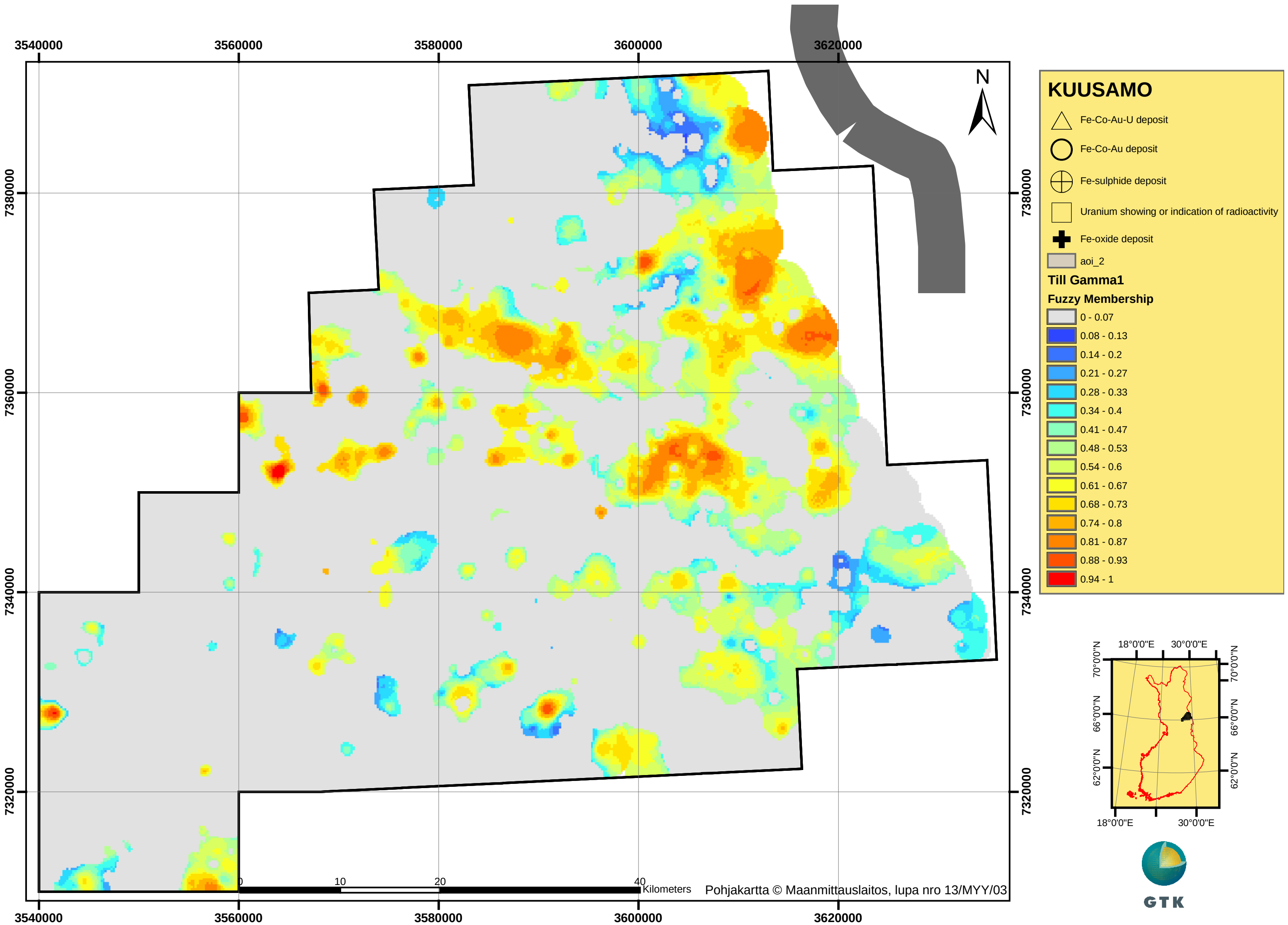


*Figure 8. Fuzzy membership values for combined till geochemistry (Till Gamma1).*

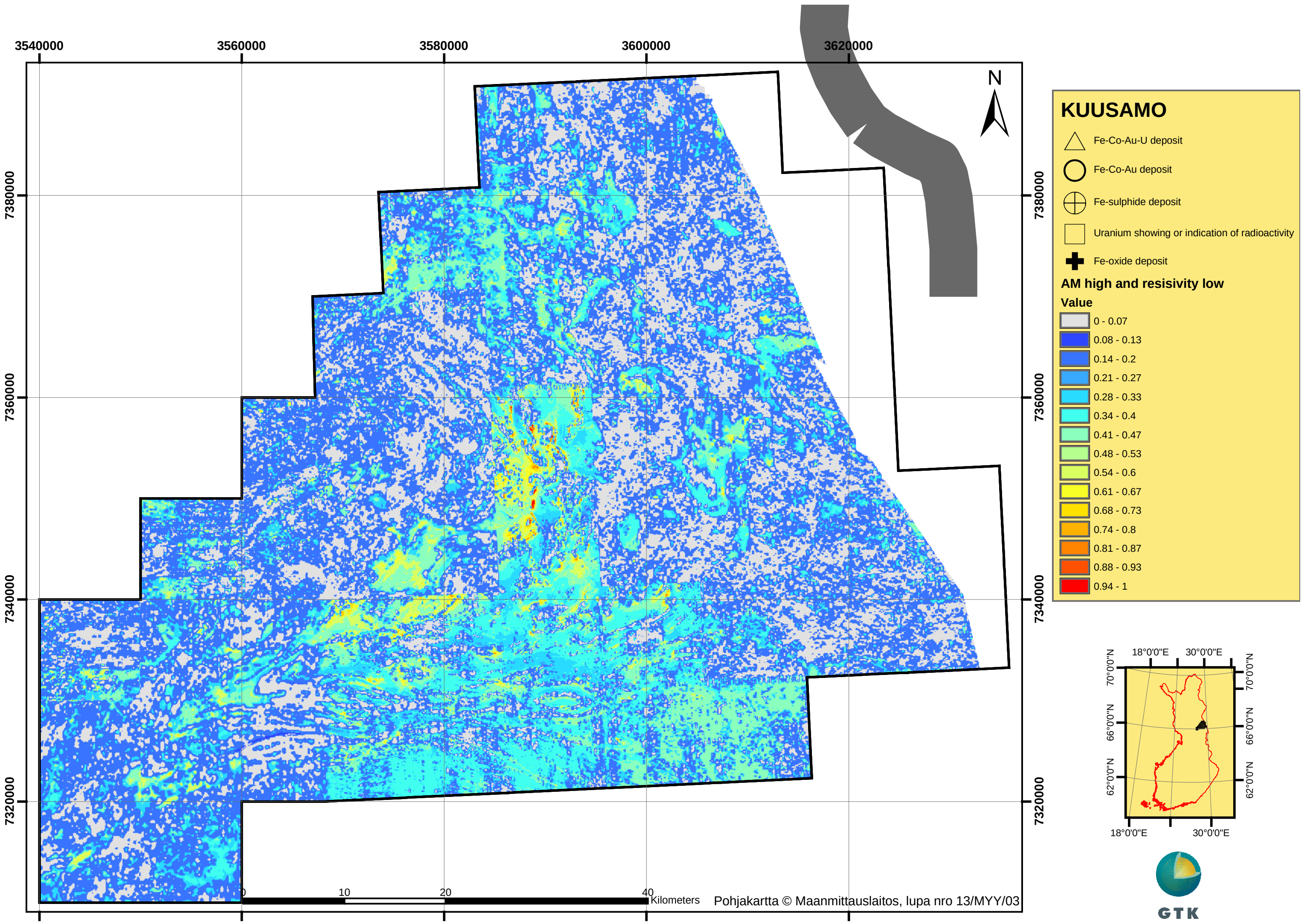


*Figure 9. Fuzzy membership values for combined AM highs and AEM real highs.*

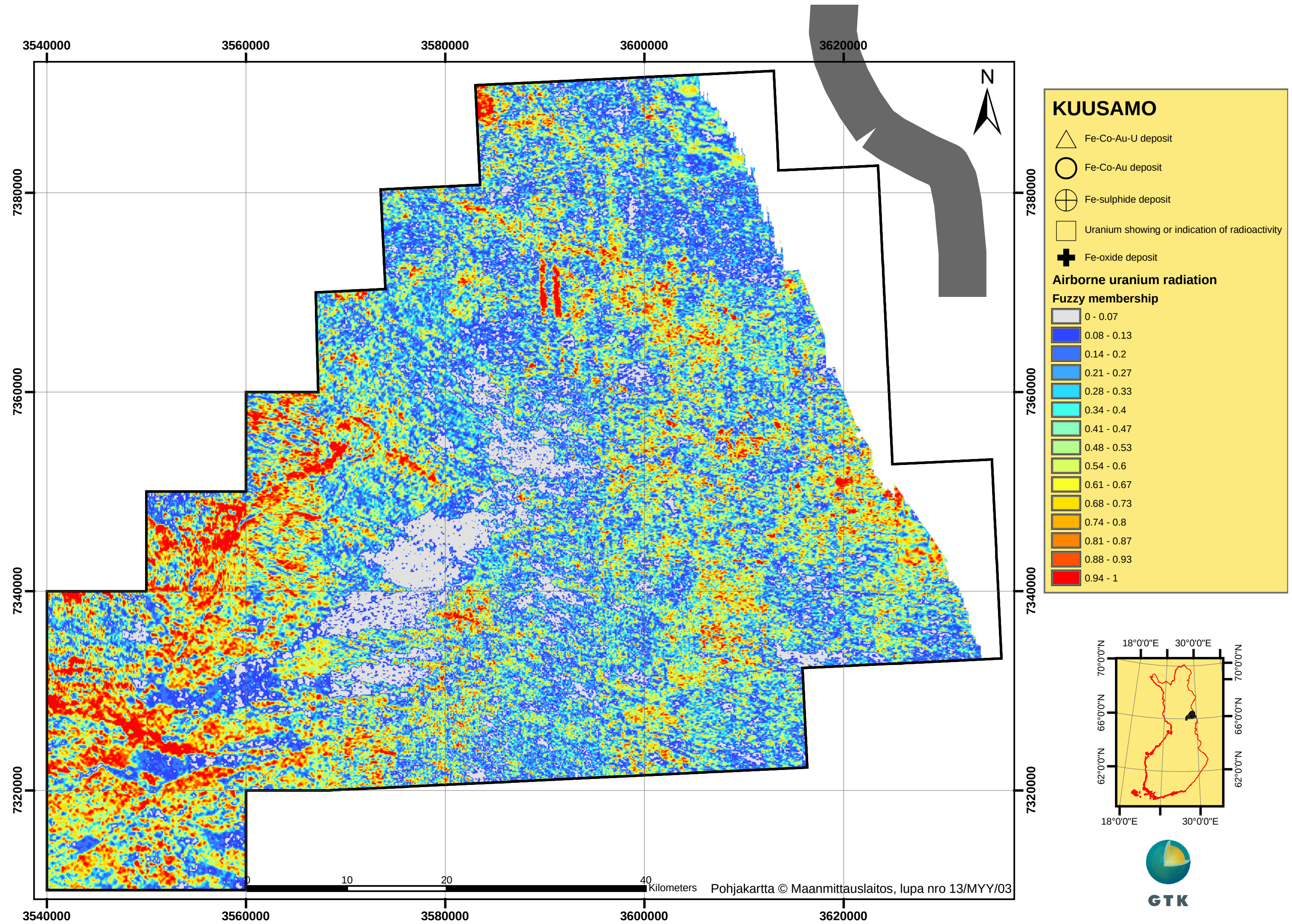


*Figure 10. Fuzzy membership values for airborne uranium radiation.*

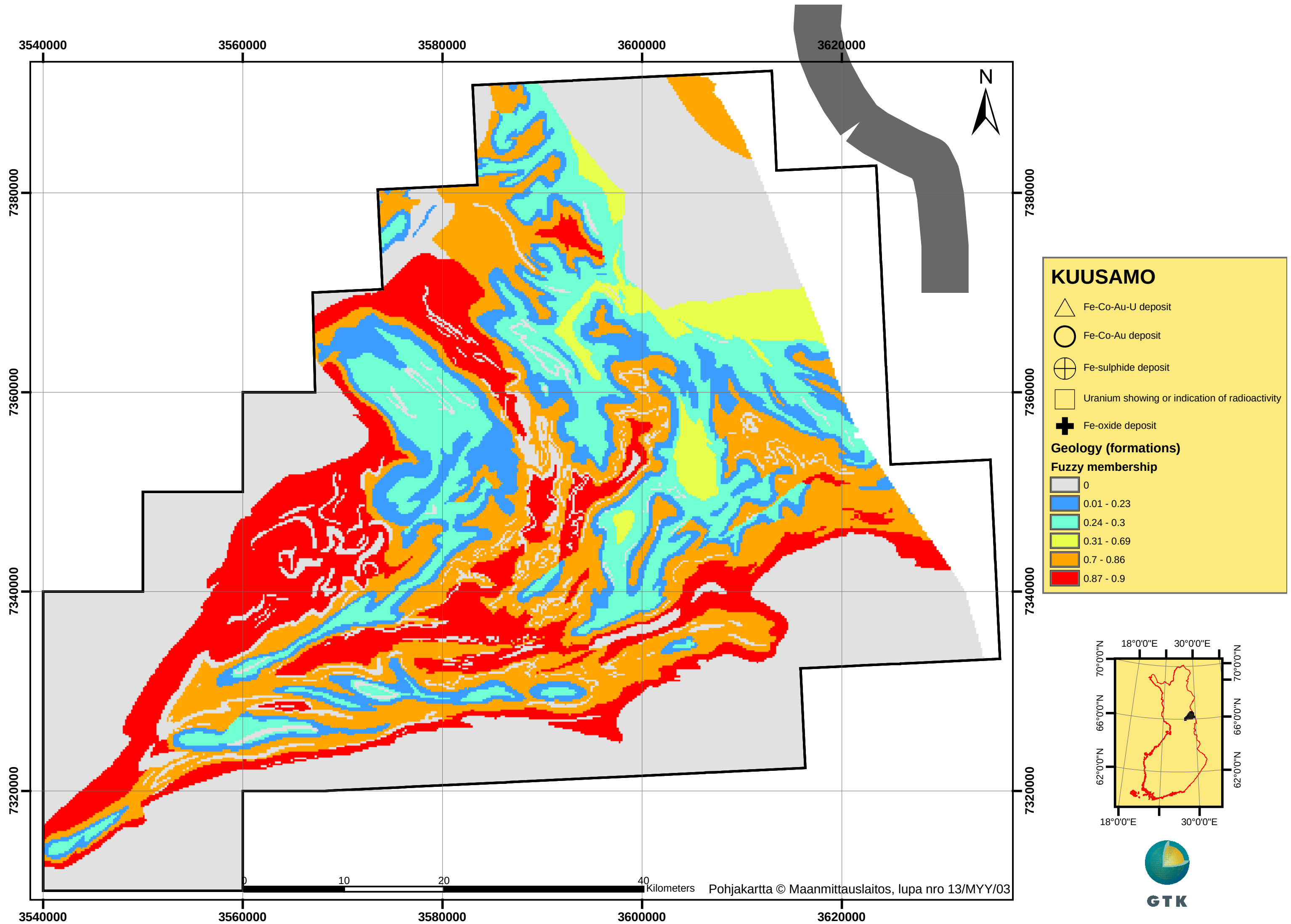


*Figure 11. Fuzzy membership values for geological formations.*

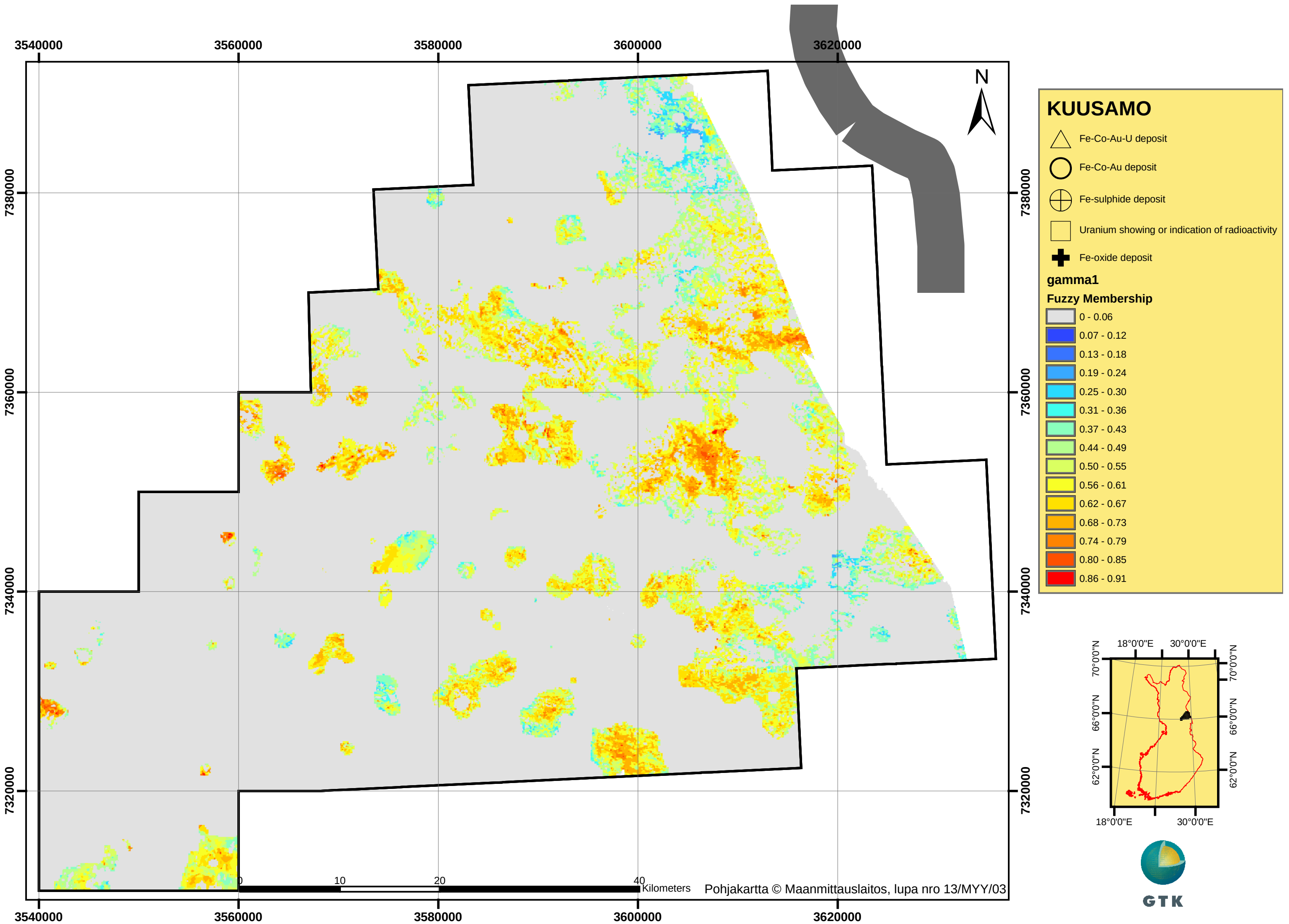


*Figure 12. Final prospectivity map Gamma1.*

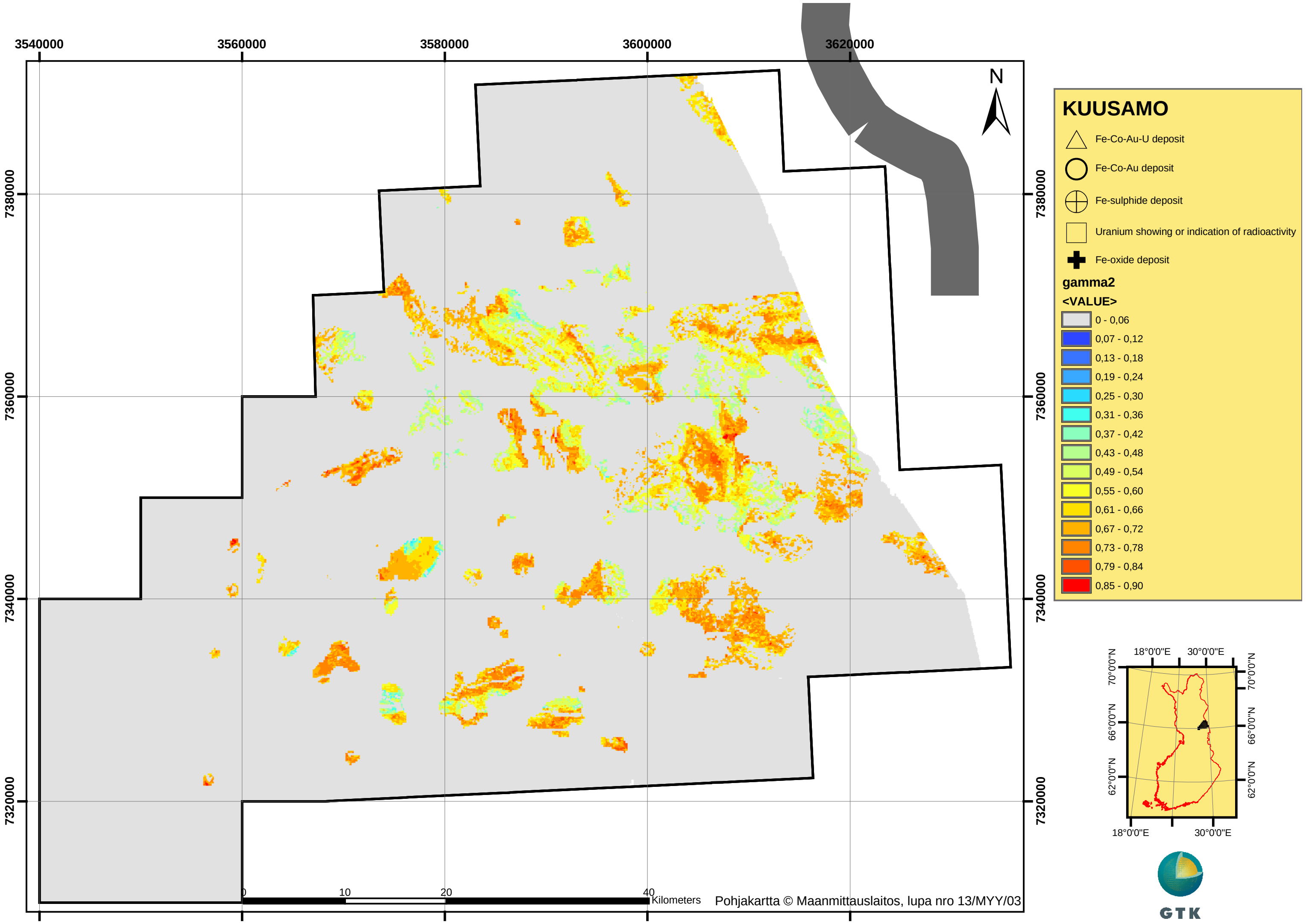


*Figure 13. A final prospectivity map Gamma2.*

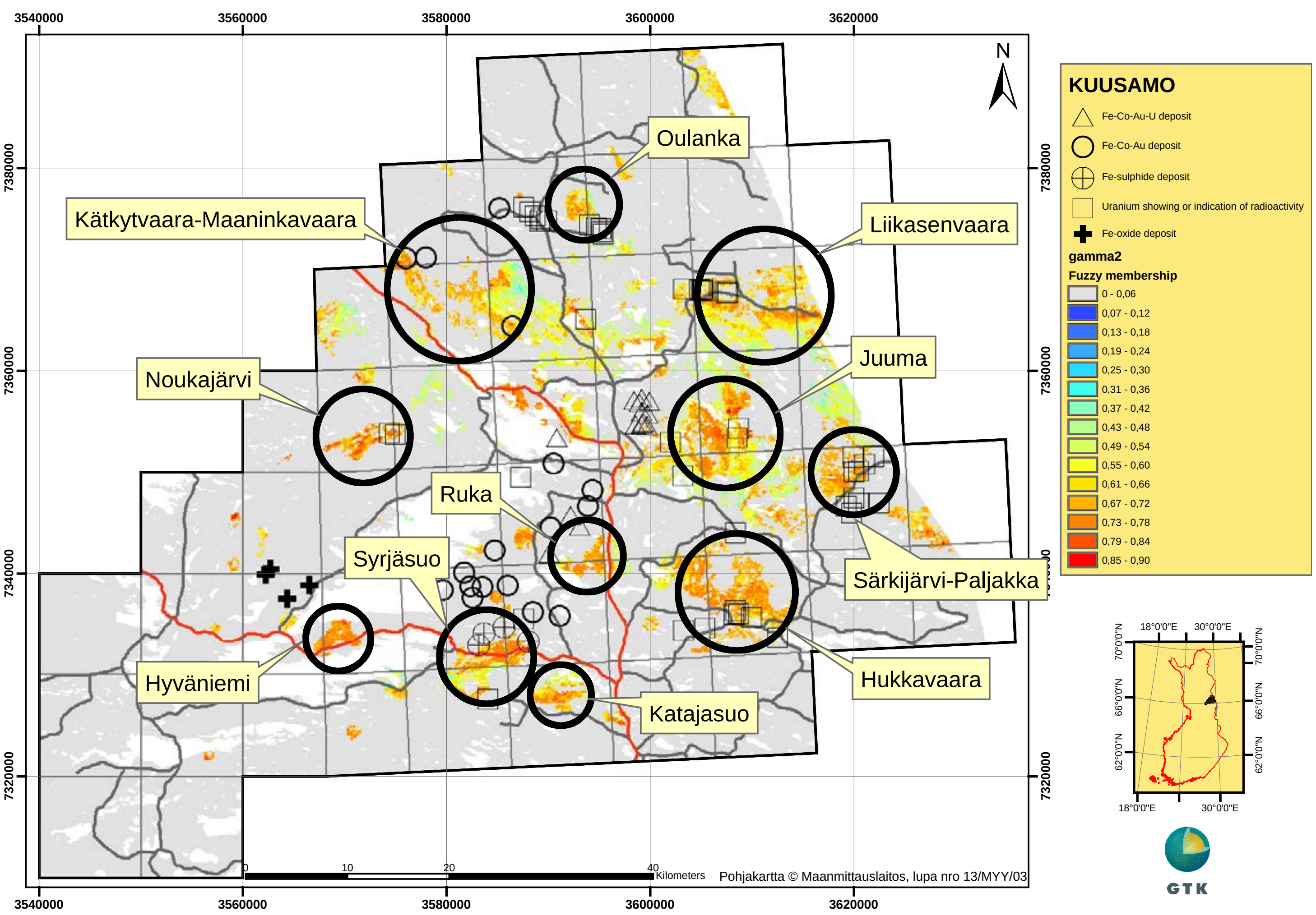


*Figure 14. A final prospectivity map (Gamma2) with the main targets pointed out and labelled.*

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