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A Geostatistical Study of Lignite Spatial Variations in the Multilayer Deposit of the Amyndeo Mine in Northern Greece

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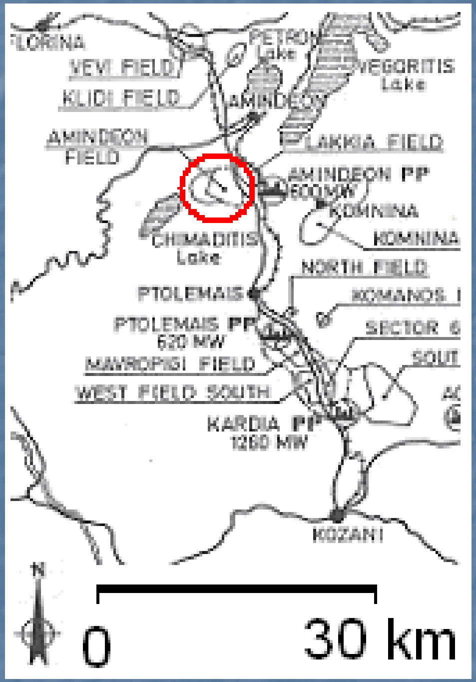
The Amyndeo mine

- Area 17 km^2 (6,6 sq. miles) with an extensive fault system. The lignite deposit is multilayered.
- PPC has produced 107 Mt since 1989
- Average annual Lignite production 8 Mt
- Estimated mean calorific value around 1200 kcal/kg

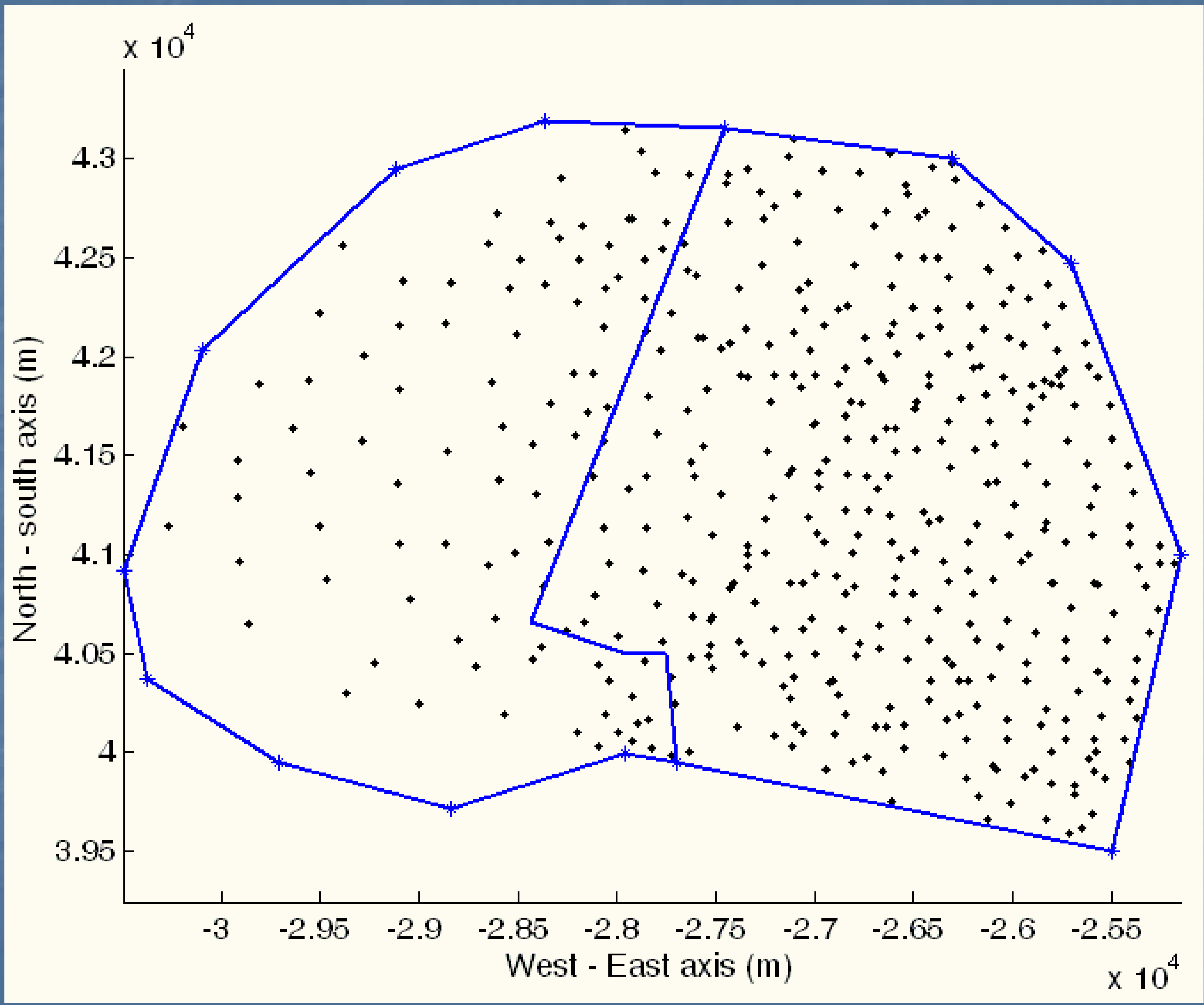


Satellite image (Google Earth)

Stages of Geostatistical study

- Exploratory statistical analysis
- Trend modelling
- Variogram estimation
- Reserves estimation
- Kriging (Spatial interpolation and mapping)

2D plot of drill hole locations



Exploratory analysis

- Drill hole data from 2 areas of the mine.
- The data used are the total thickness of lignite layers at the drill hole locations.
- Evaluation criteria: lignite layers with ash and CO_2 content over 50% or thickness less than 0.5 m are discarded.

Table of statistics

Statistics	1st dataset (exhausted)	2nd dataset (total)
Sample size	302	376
Mean (m)	13.26	14.67
Median (m)	12.85	14.10
Standard Dev (m)	7.60	8.44
Range (m)	36.60	48.00
Minimum (m)	0.50	0.50
Maximum (m)	37.10	48.50

Trend Model

$$m_{Ze}(\mathbf{s}) = 15.13 - 4.07x + 2.56y - 0.13x^2 - 1.96y^2 - 1.93xy$$

$$m_{Zt}(\mathbf{s}) = 18.61 - 4.95x + 2.31y - 1.97x^2 - 2.17y^2 - 1.22xy$$

- Correlation coefficient of trend with 1st dataset

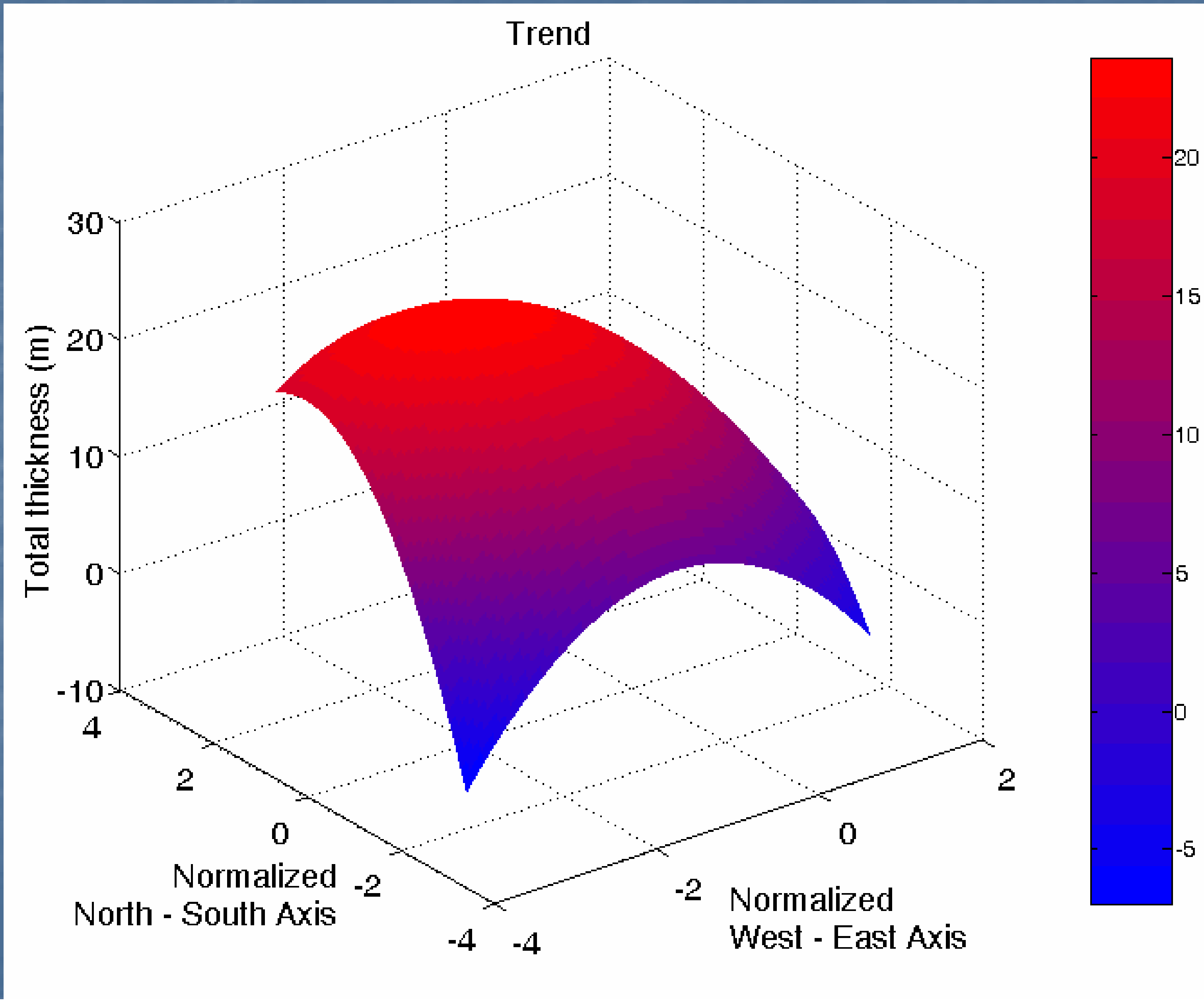
  $\rho_{z,me} = 67.4\%$

- Correlation coefficient of trend with 2nd dataset

  $\rho_{z,mt} = 65.2\%$

- The fluctuations $\mathbf{X}_i = \mathbf{Z}_i - \mathbf{m}_Z$, do not follow the normal distribution in either datasets (based on the Lilliefors test at the 10% significance level).

Lignite thickness trend

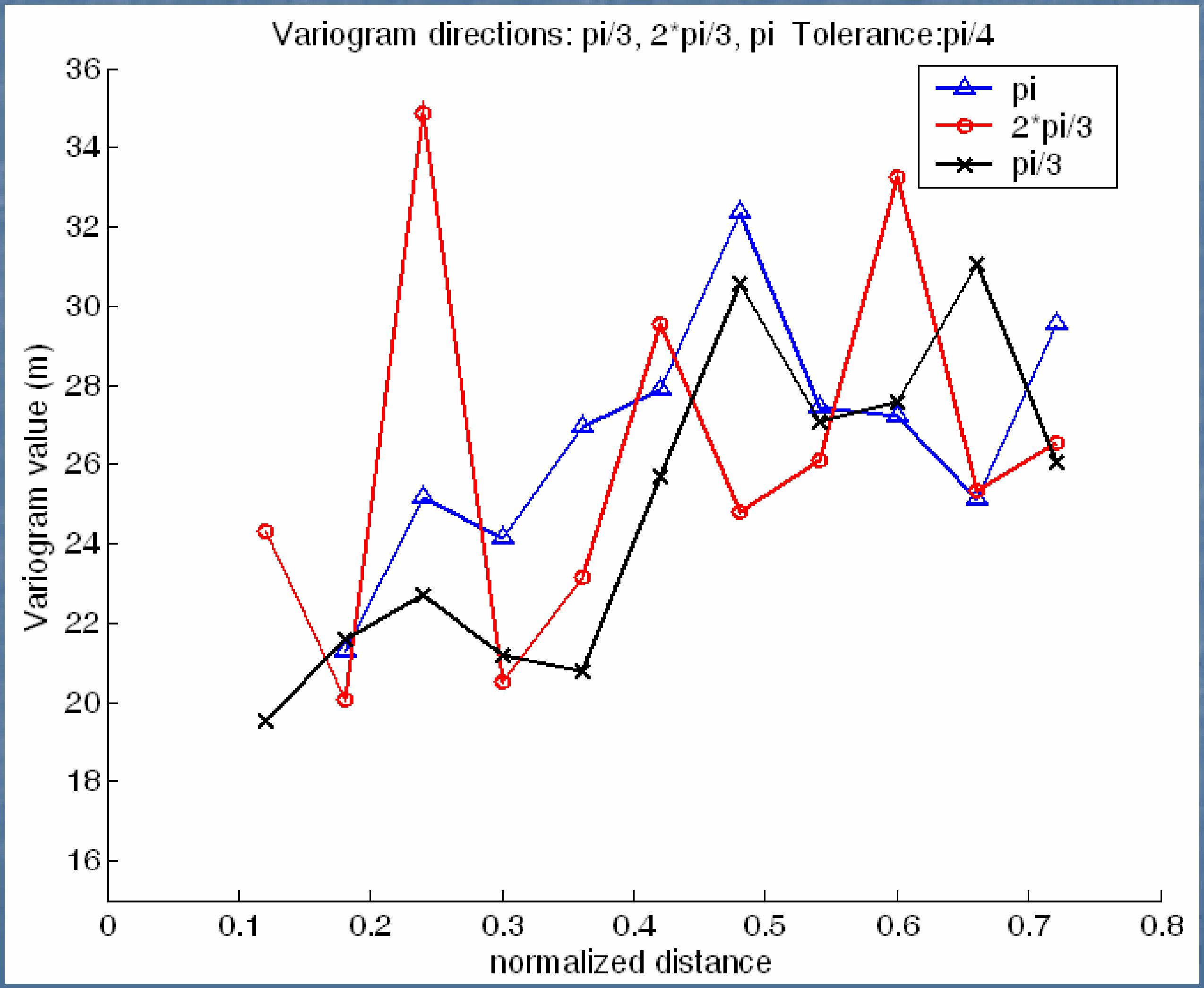


Variogram estimation for the exhausted part of the mine

- The robust estimator (Cressie and Hawkins, 1980) of the experimental variogram is used to reduce impact of extreme values.
- The semivariogram plots for the exhausted area suggest geometric anisotropy.
- The method of maximum likelihood is used to fit the variograms to an anisotropic exponential model.

Anisotropic ratio	1.90	ξ_x	0.210	C_0 (m)	2.65
φ	99.4°	ξ_y	0.399		

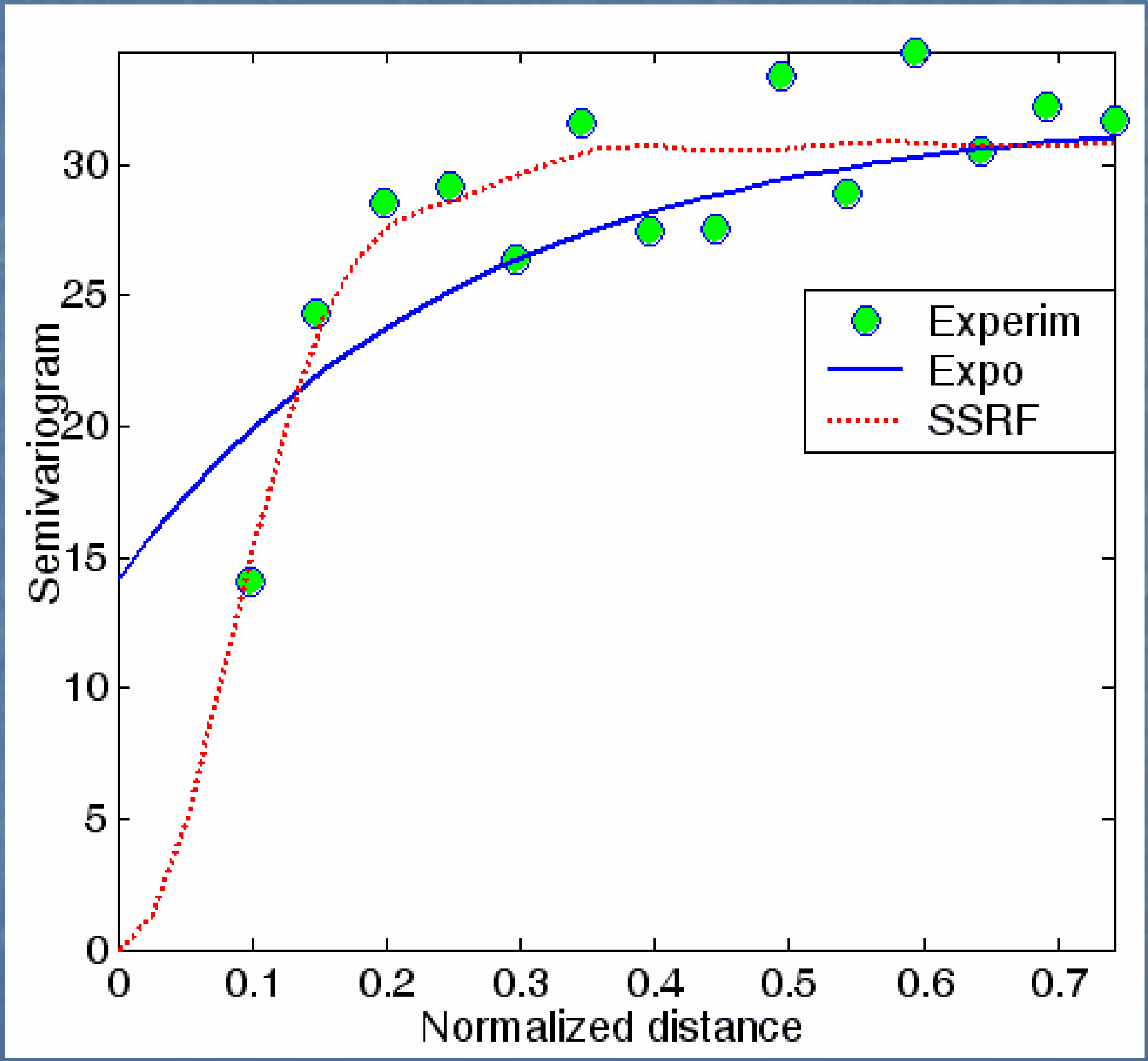
Variogram plots for the exhausted part of the mine



Variogram estimation for the whole mine

- The semivariogram plots for the total mine area do not suggest geometric anisotropy.
- From the directional semivariograms, the anisotropy ratio is estimated to be from 1.45 to 1.7.
- The omnidirectional experimental variogram is calculated.

Variogram plots for the total mine area



Variogram models

- Exponential model:

$$\gamma(\mathbf{r}) = c_0 + \sigma^2 \left[1 - \exp(-\|\mathbf{r}\|/\xi)\right]$$

ξ	σ^2 (m)	C_0 (m)
0.26	17.97	14.17

- Spartan model:

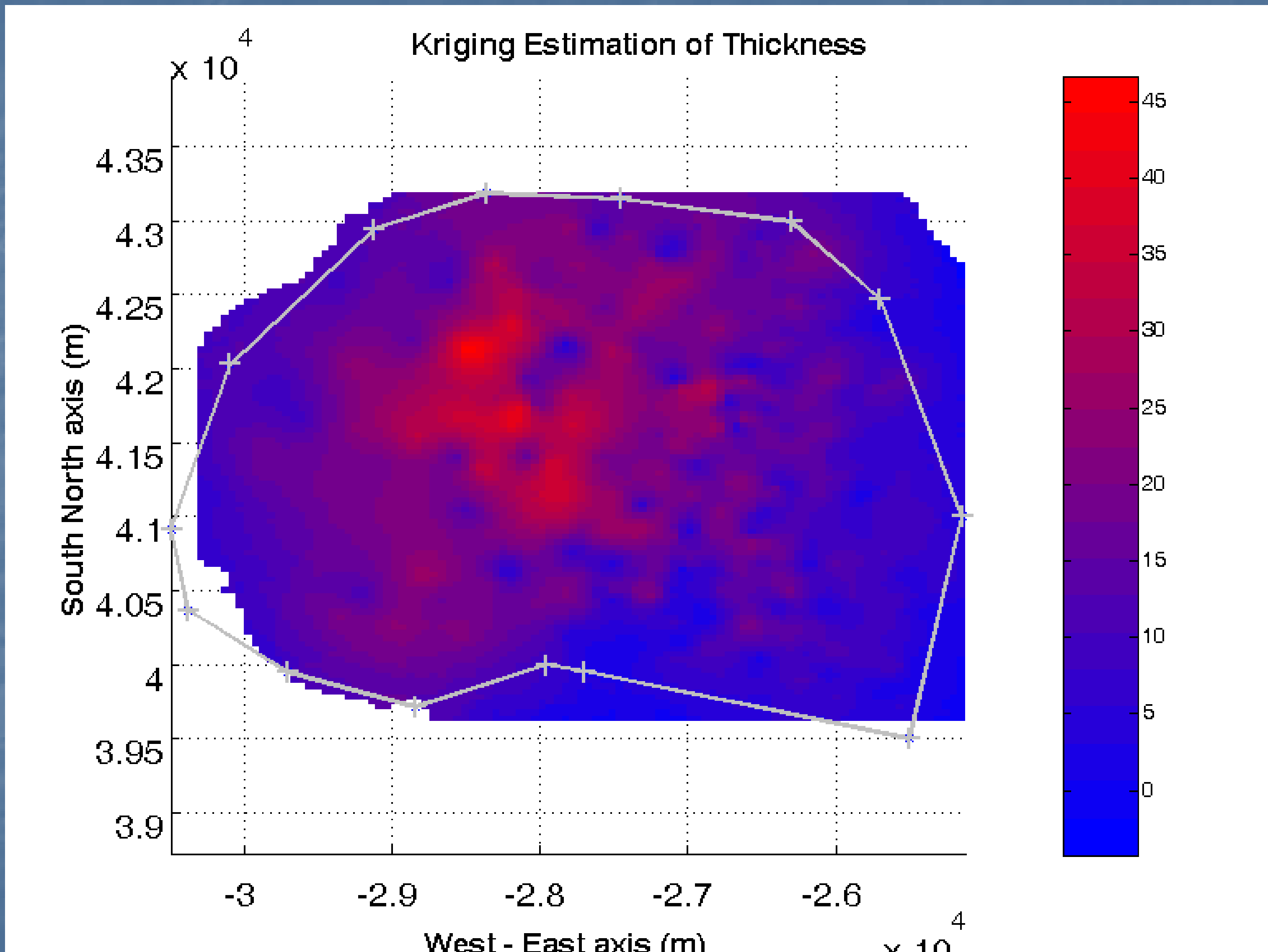
$$\gamma(\mathbf{r}) = \frac{\eta_0 \xi^2}{2\pi} \int_0^{k_c} dk \, \frac{k\left[1 - J_0(kr)\right]}{1 + \eta_1 \xi^2 k^2 + \xi^4 k^4}$$

η_0	η_1	ξ	k_m
514.92	2.26	0.06	32.13

Spatial interpolation

- Maps of estimated lignite thickness and estimate precision are generated with Ordinary Kriging using the exponential variogram.
- The map is generated on a 100 x 100 grid. Each grid cell is 50.8m x 34.8m.
- Correlation coefficient between actual and estimated values is 68.4%.
- Estimation of reserves using this grid is 205 Mt.

Estimated lignite thickness (m)



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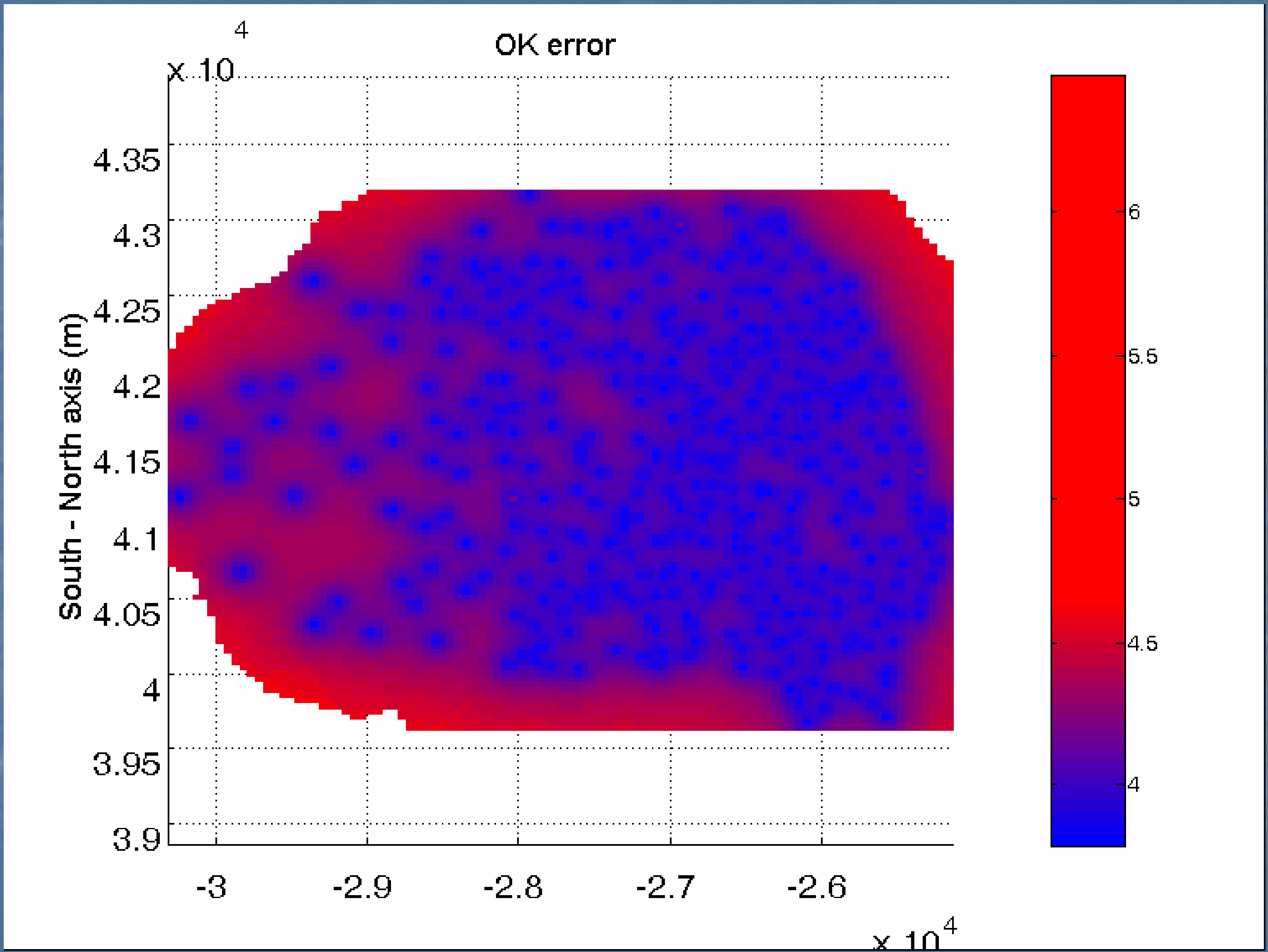
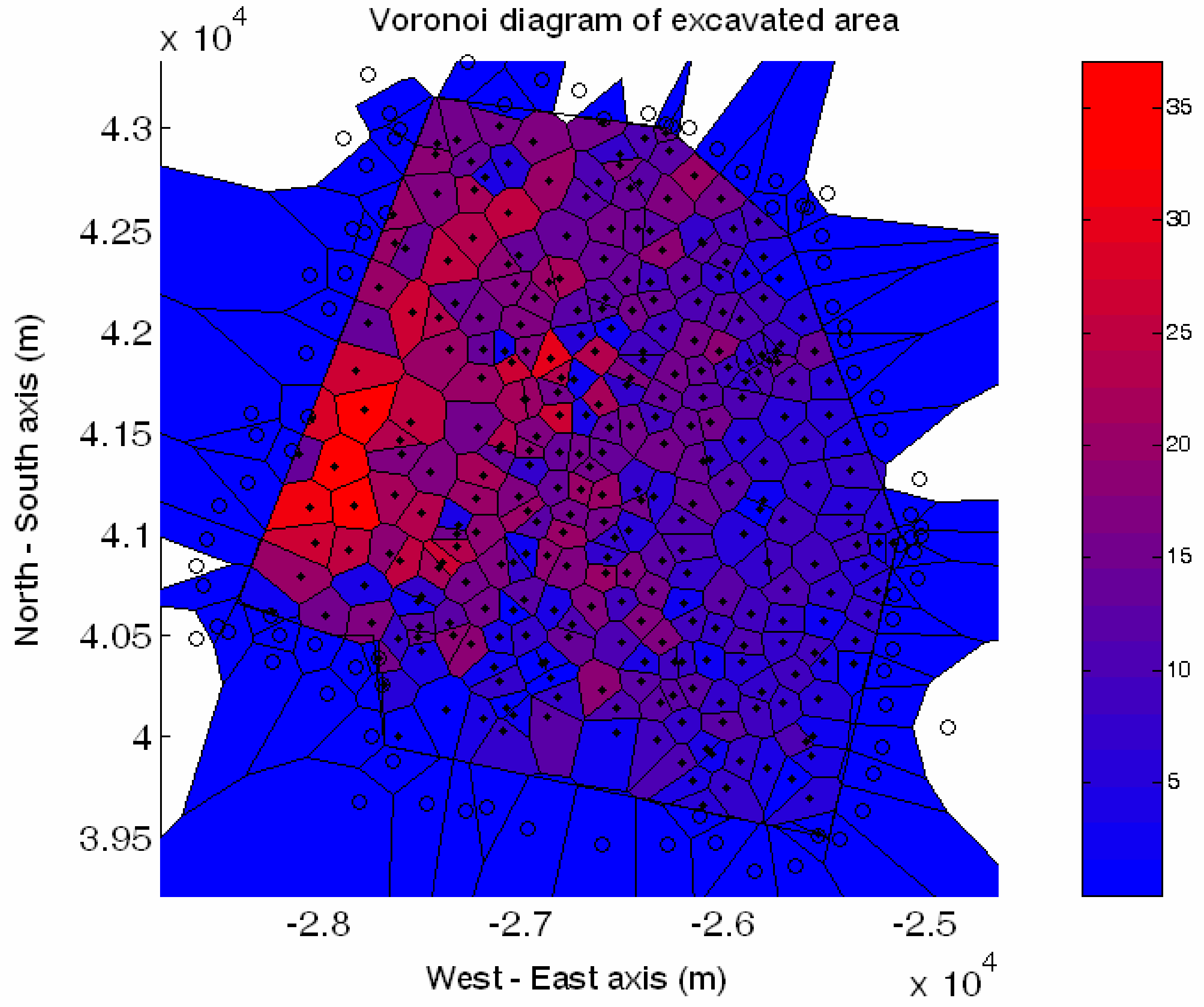
Kriging standard deviation (m)



Reserves Estimation

- Voronoi diagrams are used to estimate mine reserves.
- Each point of the study area is considered to have the total thickness of the lignite layers of the nearest drill hole.
- A group of mirror points is used to close the Voronoi polygons at the boundaries of the study area.

Reserves estimation in excavated area

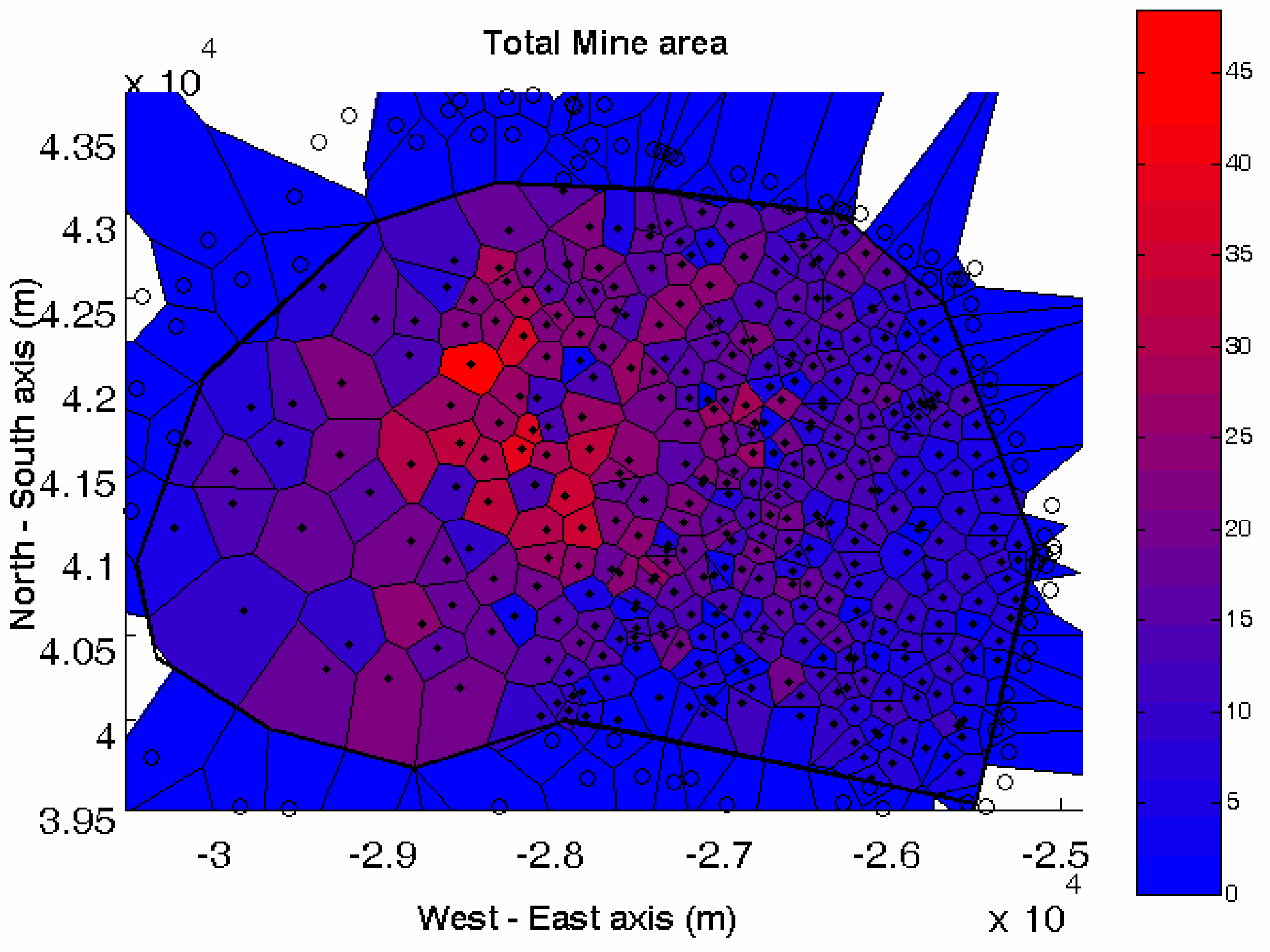


Estimation: 125 Mt

PPC data: 105 Mt

Overestimation is about 20%.

Total reserves estimation



- Initial Estimation: 287 Mt
- Assumed overestimation: 55 - 60 Mt
- Final estimation: 230 Mt

Conclusions

- The Voronoi diagrams give a reasonable first estimate of the lignite reserves even with a restricted set of drill hole evaluation criteria.
- The OK precision is not satisfactory. Partly because of the non-Gaussian distribution of the lignite thickness, partly because of the faults of the area.

Suggestions for further analysis

- Incorporation of a more complete set of drill hole evaluation criteria.
- Modelling non-Gaussian thickness fluctuations.
- Application of the Spartan Random Fields model for Ordinary Kriging (using a denser drill hole grid that will be available in the near future).
- Creation of Kriging estimation maps on other lignite properties like flying ash content and calorific value.
- Using constrained Voronoi diagrams to better account for the presence of the faults.

Thank you!

Acknowledgments

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Robust estimator (Cressie and Hawkins, 1980)

$$\gamma_{\exp}(\mathbf{r}) = \frac{\left[\sum_{i=1}^{N_{\mathbf{r}}} \sqrt{\left|Z(\mathbf{s}_i) - Z(\mathbf{s}_i + \mathbf{r})\right|} \Big/ N_{\mathbf{r}}\right]^4}{2\left(0.494/N_{\mathbf{r}} + 0.457\right)}$$

Variance of Ordinary Kriging estimation

$$\sigma_{OK}^2(\mathbf{s}_u) = \sum_{i=1}^{4} \lambda_i \gamma(\| \mathbf{s}_u - \mathbf{s}_i \|) + \mu$$

$$\sum_{i=1}^{4} \lambda_i = 1$$