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Spatial analysis of hydraulic conductivity for slope deposits at catchment scale in Northern Tuscany, Italy

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• **Objectives**

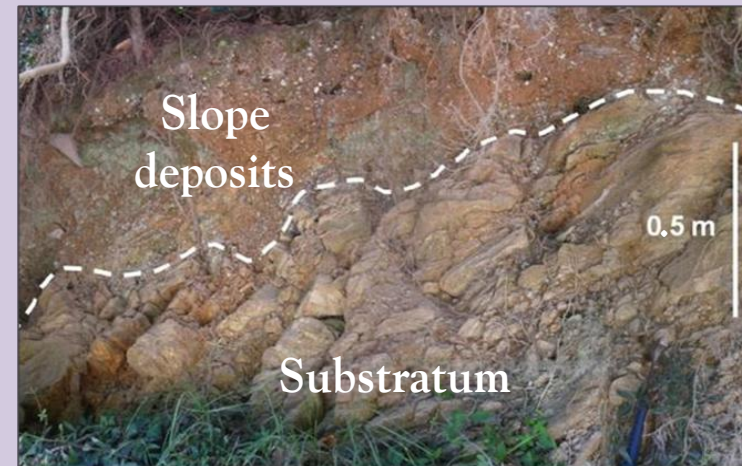
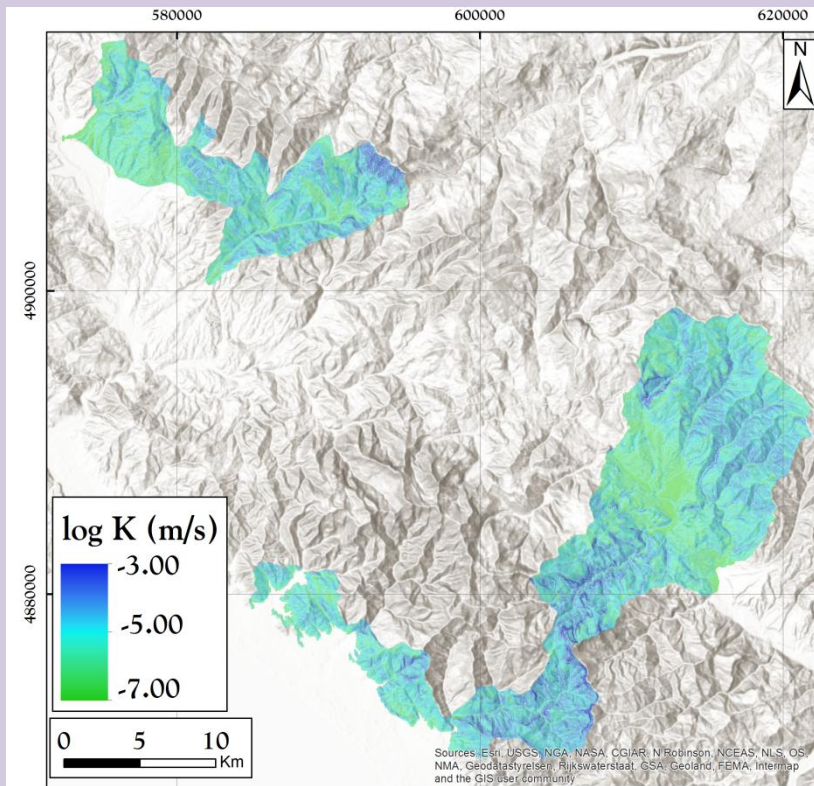
• Materials and methods

• Results

1. Grain size
2. Characterization of K
3. Geostatistical analysis
 - 3.1 Horizon 1
 - 3.2 Horizon 2
 - 3.3 All Ktests

• Conclusions

Analysis of site-variability and spatial distribution at catchment scale of hydraulic conductivity of slope deposits (SD)



Slope deposits are **unconsolidated** (Quaternary) **soils** that unconformably cover the geological substratum



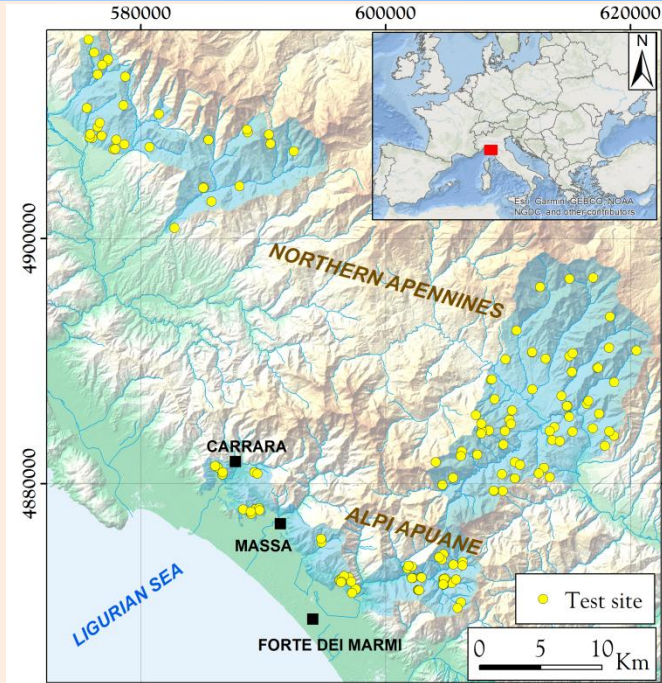
Study area is represented by 2 regions (420 km²) in Northern Tuscany (Italy)

Field survey

- ✓ **Trench** within SD (depth, texture, structure, soil sampling)
- ✓ **Hydraulic conductivity tests** (Ktests) within 1-5 boreholes close (≤ 10 m) to the trench. Ktests performed by using **constant** and **falling** head permeameters (*LeFranc* tests)

Laboratory

- ✓ Grain size, Atterberg limits, specific gravity of solids, bulk density



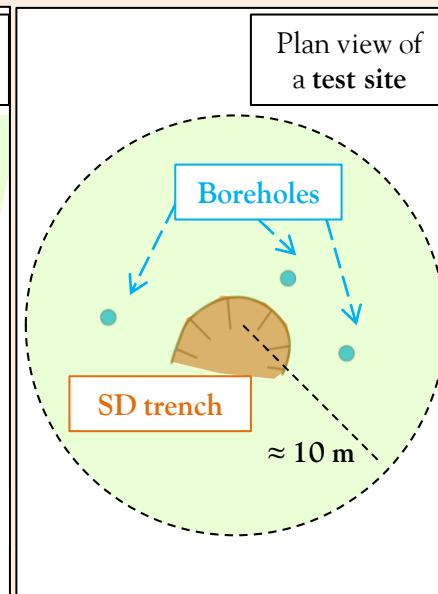
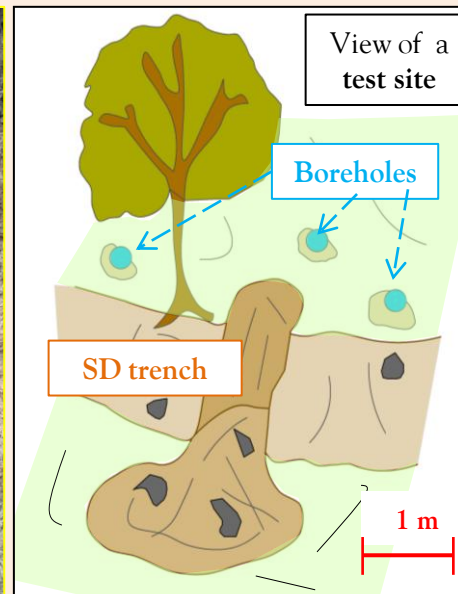
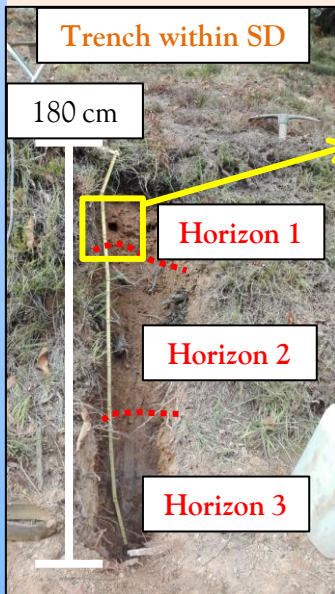
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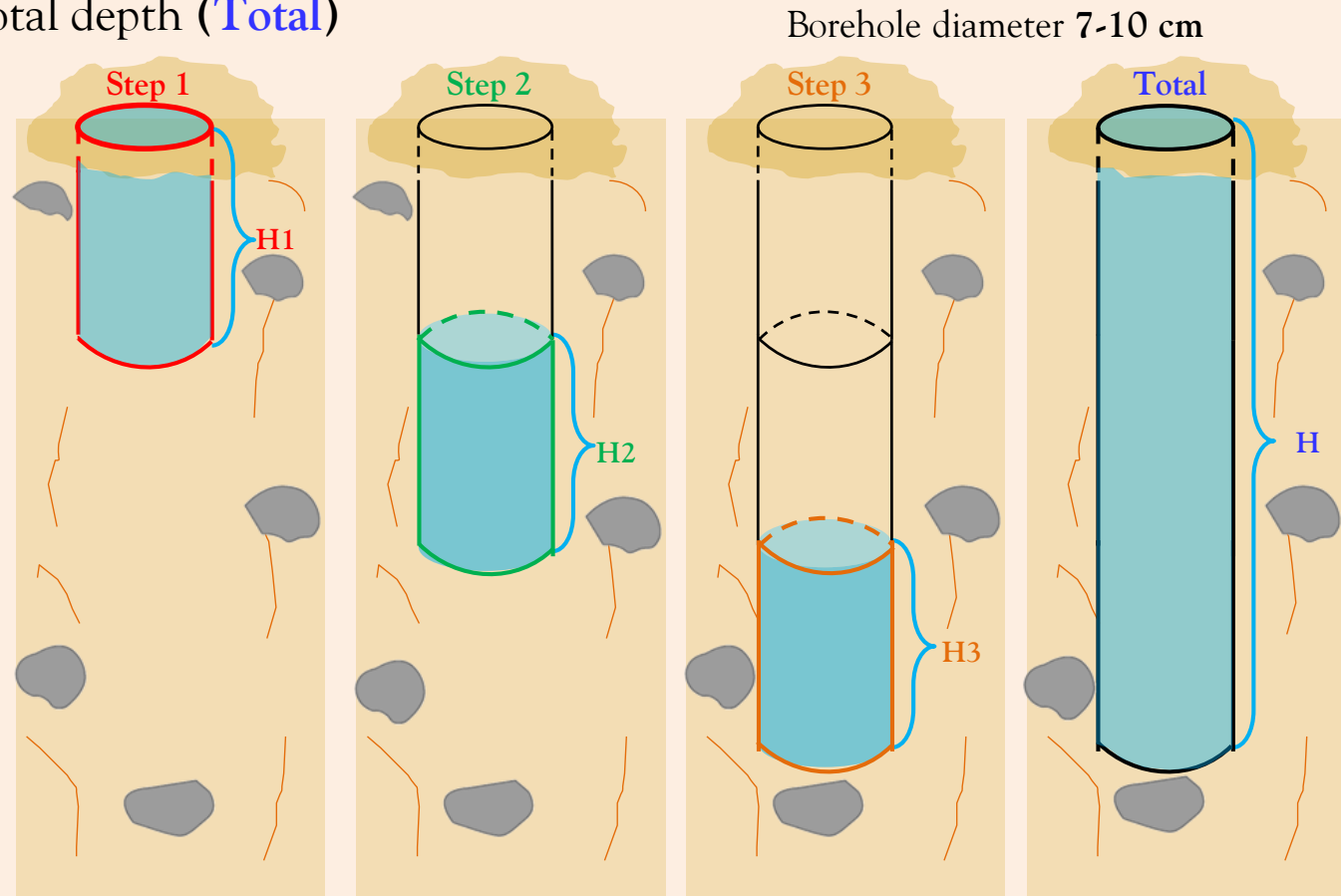


Field survey: Ktests

A total of 721 Ktests (150 test sites) have been performed following this approach:

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- steps of increasing borehole depth (**Step 1**, **Step 2**, **Step 3**, Step n....) in order to evaluate variation of K with depth
- total depth (**Total**)

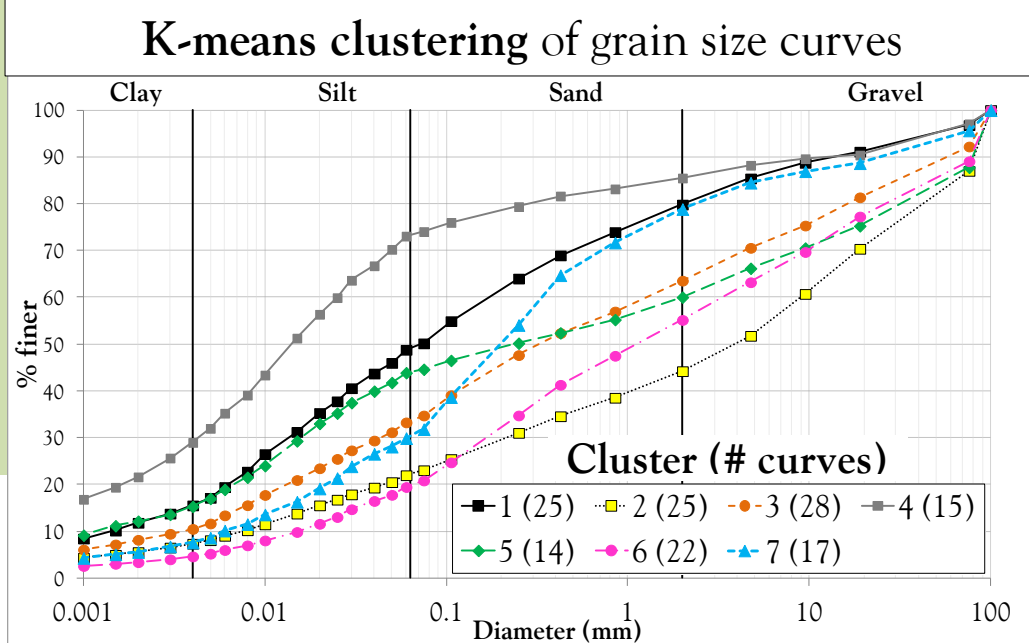




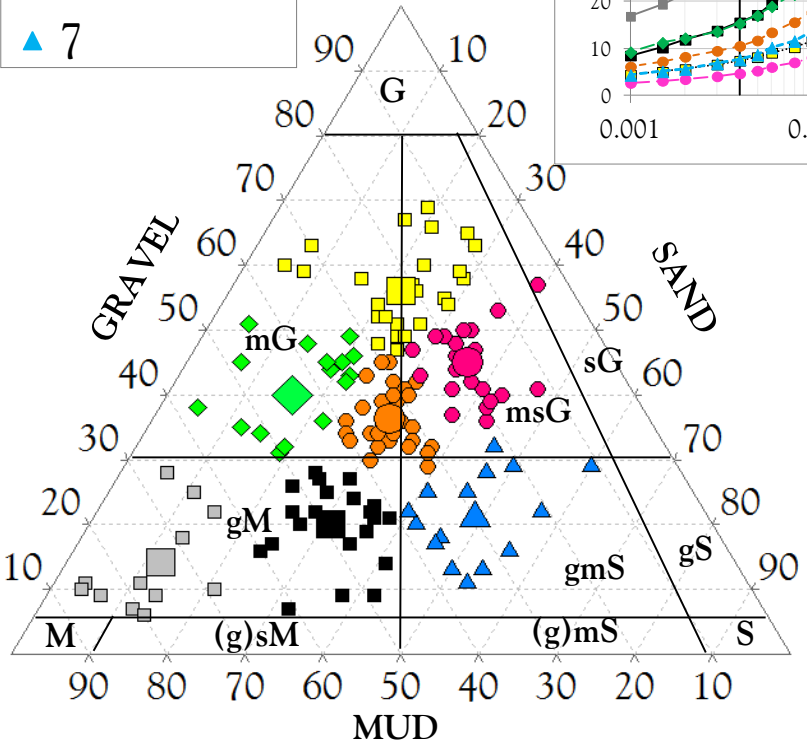
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Grain size data - 146 samples

$C_u (d_{60}/d_{10})$	
Interquartile range	Range
80-630	7-38,000



Clusters		
■ 1	■ 2	● 3
■ 4	◆ 5	● 6
▲ 7		

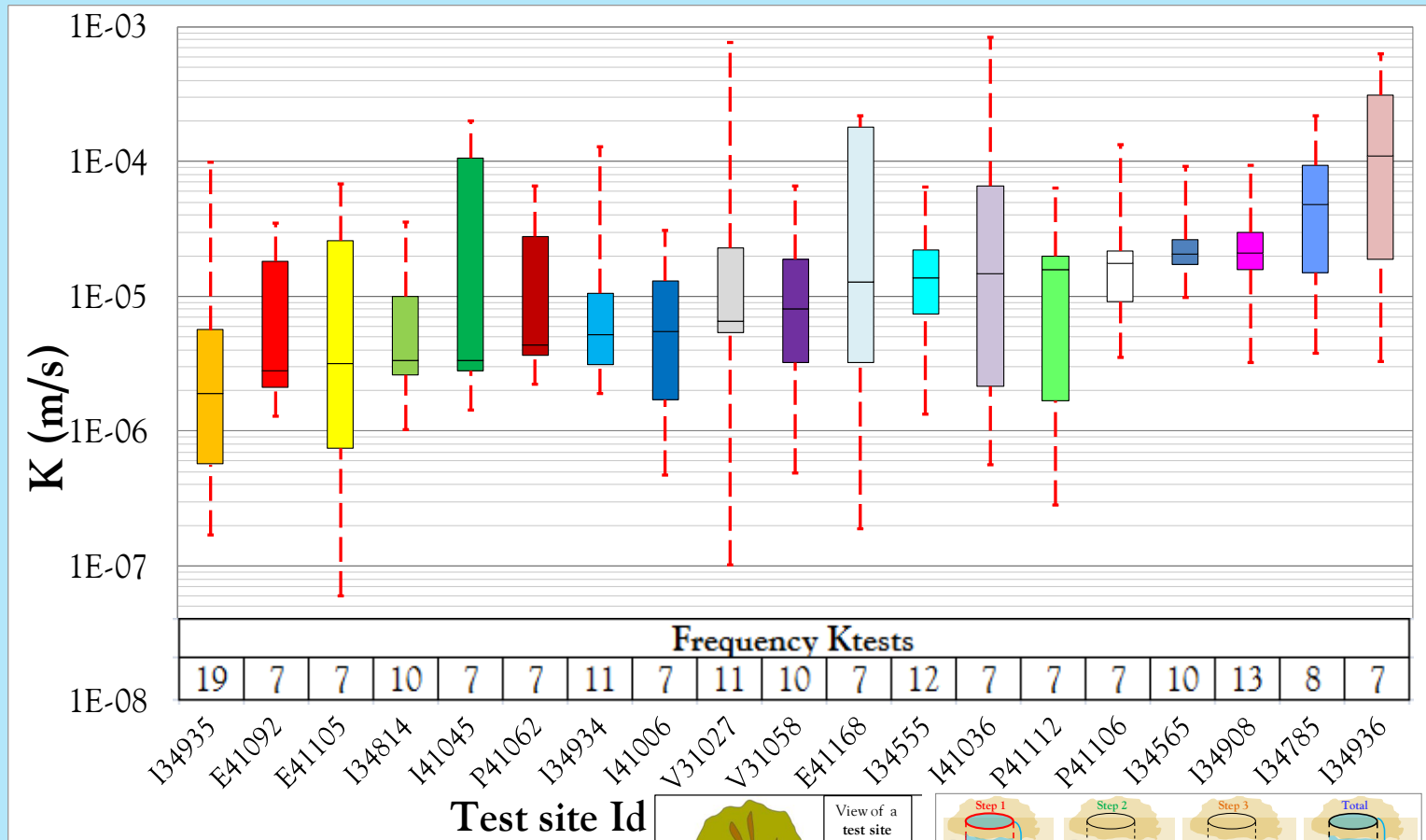


Frequency (%)	Texture Class	Description
34	mG	muddy Gravel
30	msG	muddy sandy Gravel
24	gM	gravelly Mud
12	Others	-



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Site variability of hydraulic conductivity

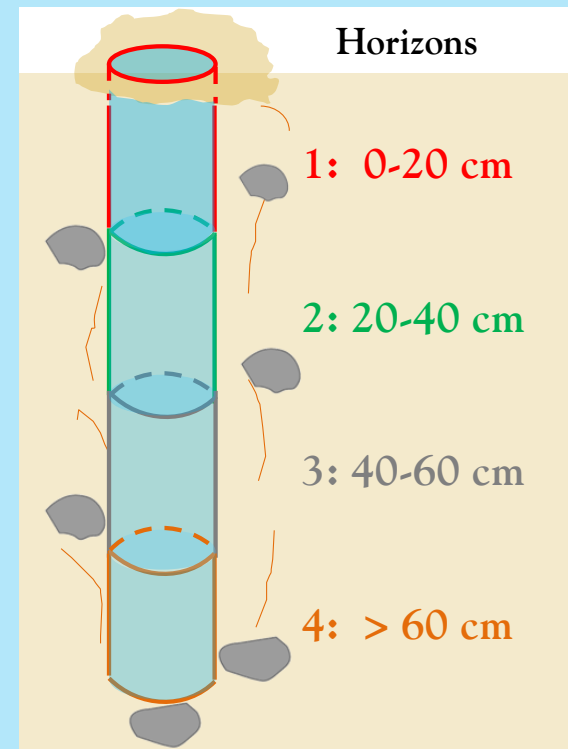
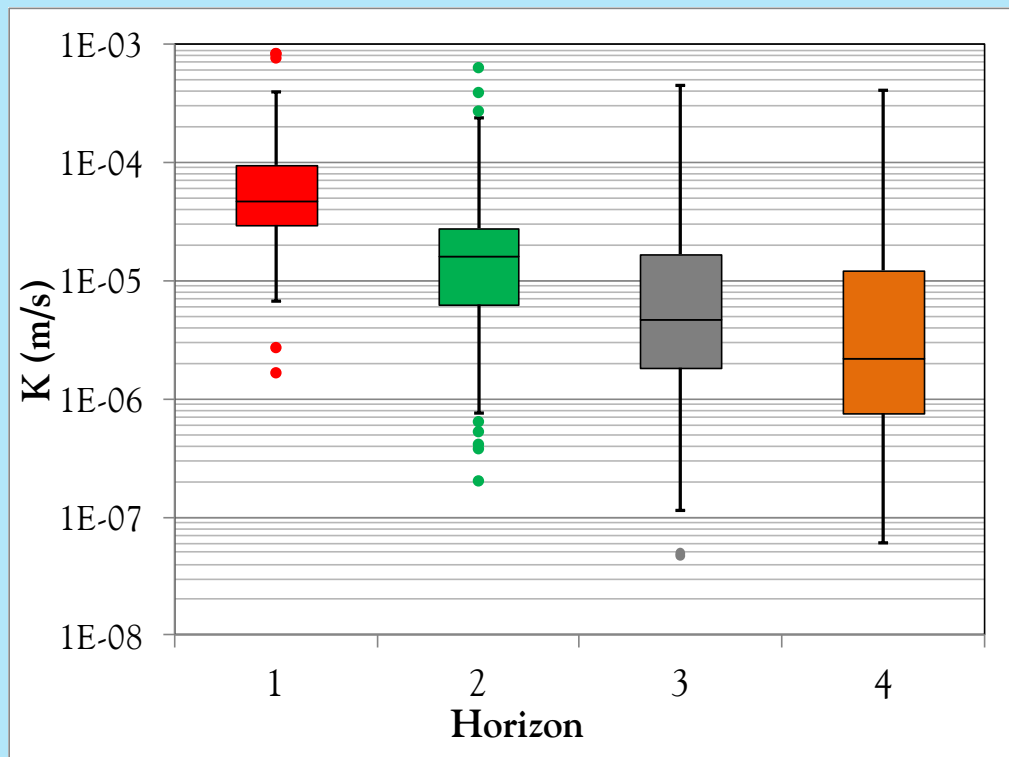


log K (m/s)	
Median of Interquartile range	Median of Range
0.8	1.9

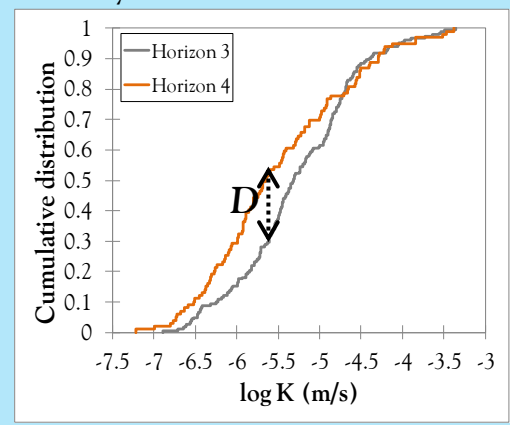
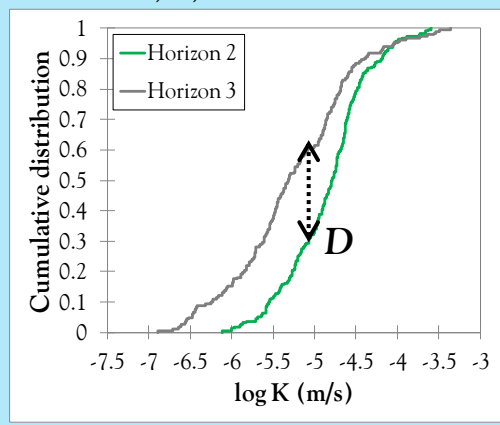
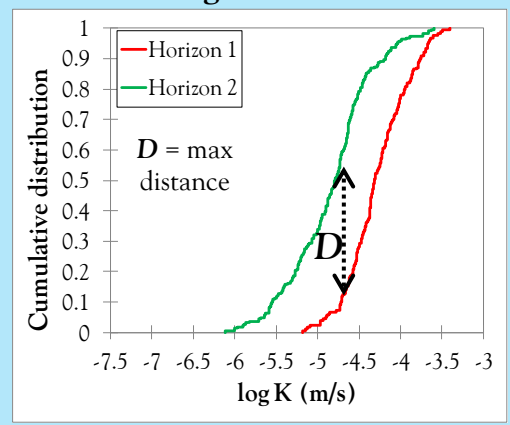


Hydraulic conductivity by horizons

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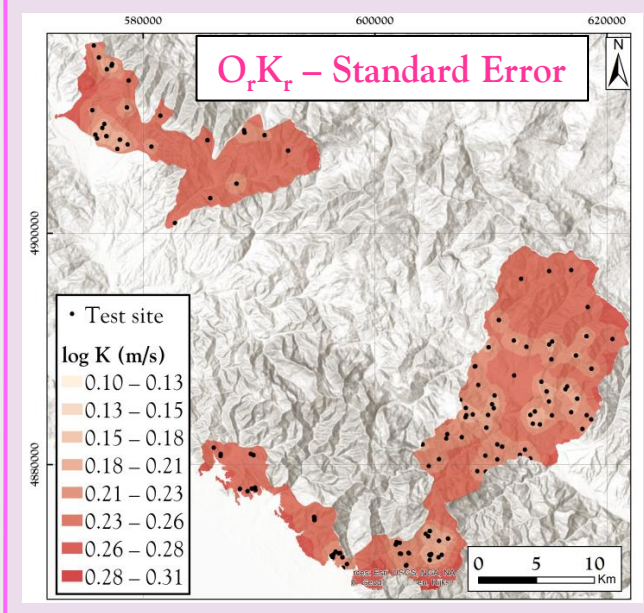
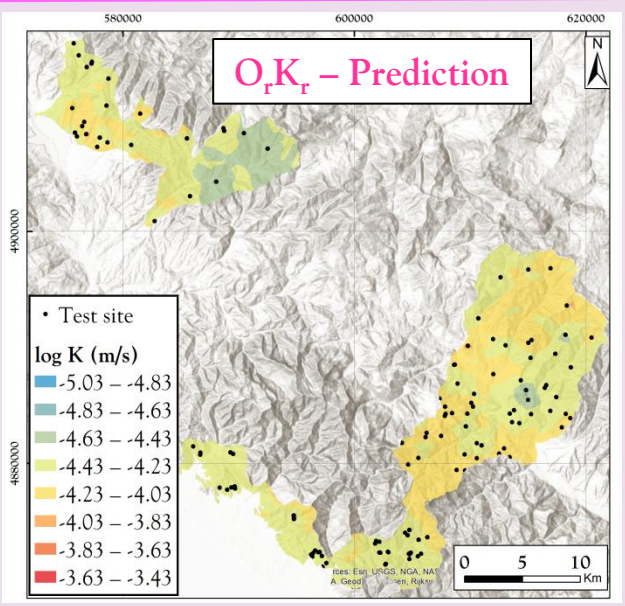
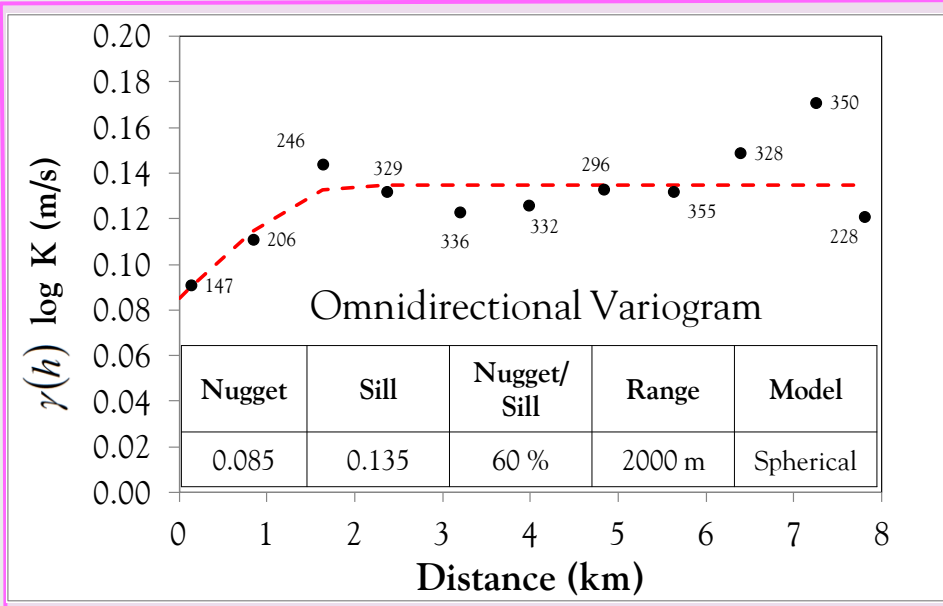
Kolmogorov-Smirnov test: horizons 1, 2, 3 and 4 are **ALL** statistically each other different



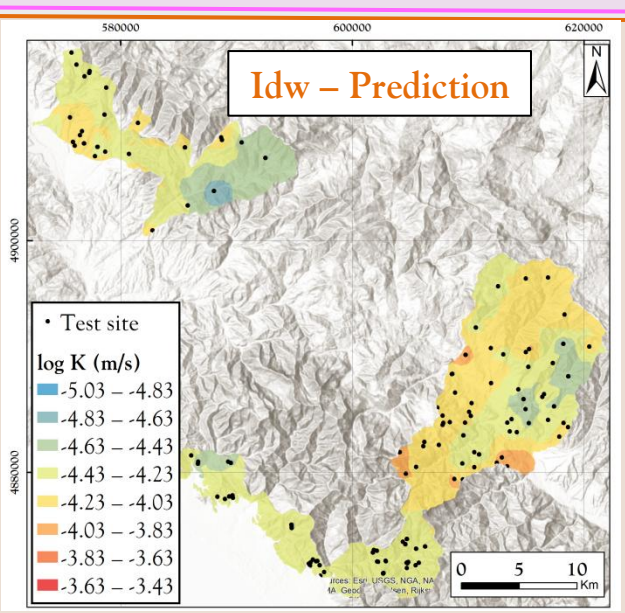
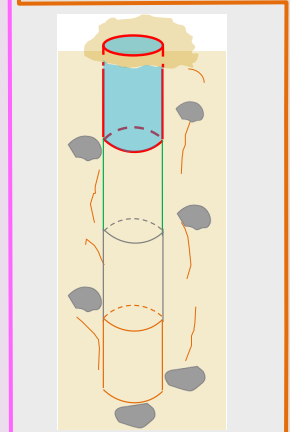


Horizon 1 (0-20 cm) – Ordinary Kriging (O_rK_r) and Inverse Distance Weighting (Idw)

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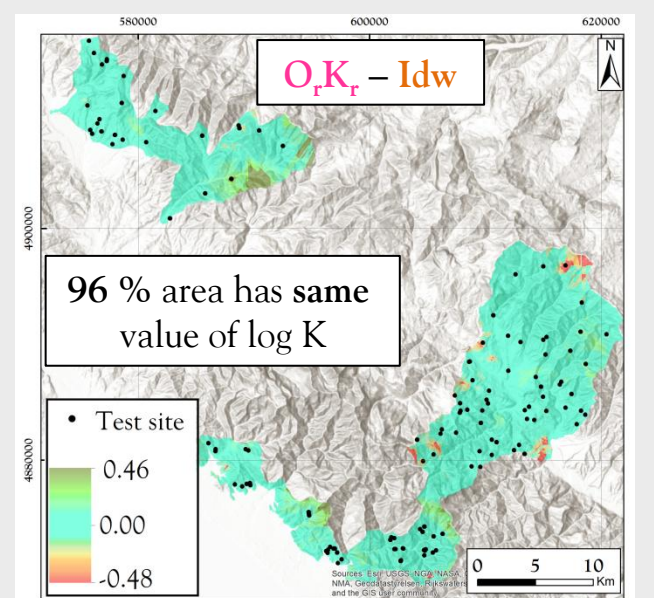
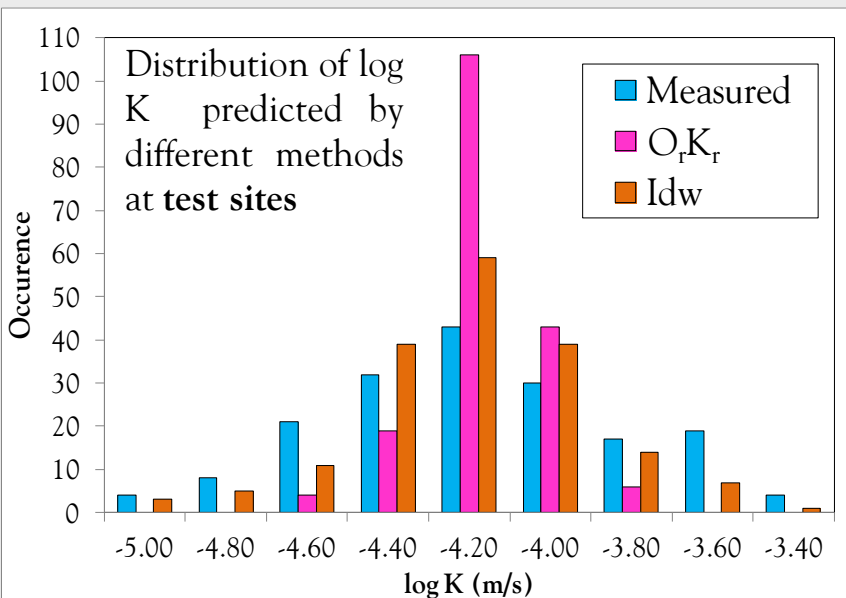
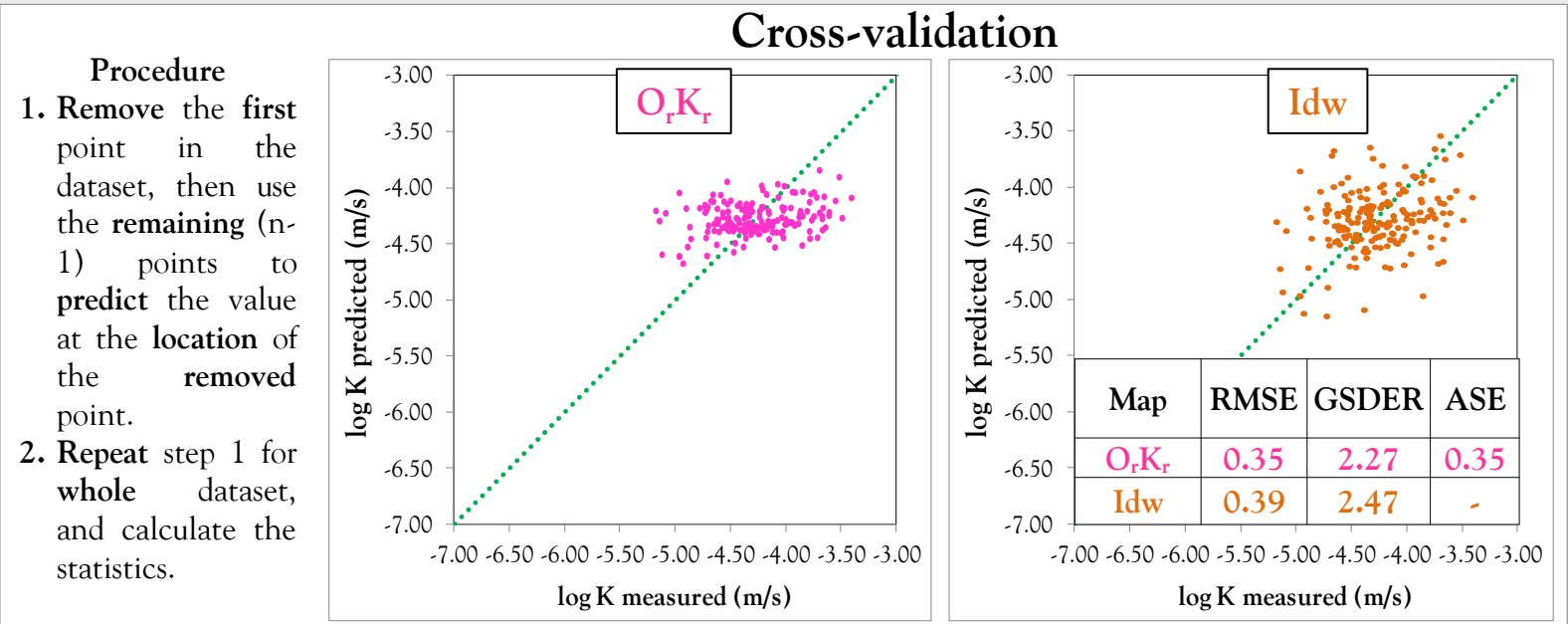
Power	1
Range	2500 m





Horizon 1 (0-20 cm) – Ordinary Kriging (O_rK_r) and Inverse Distance Weighting (Idw)

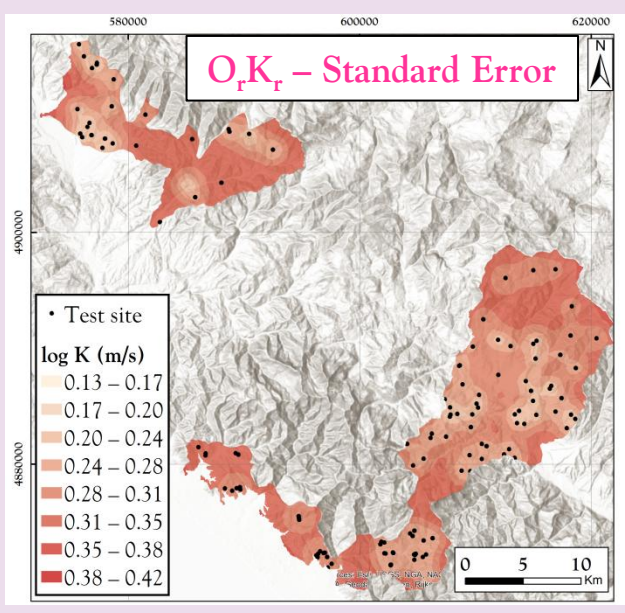
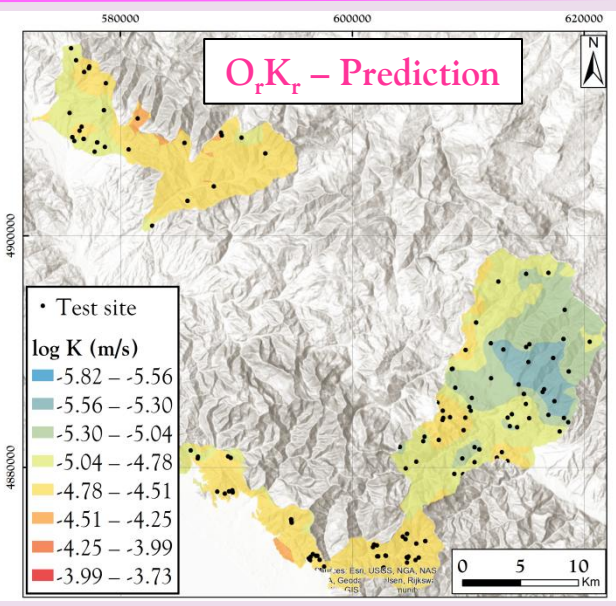
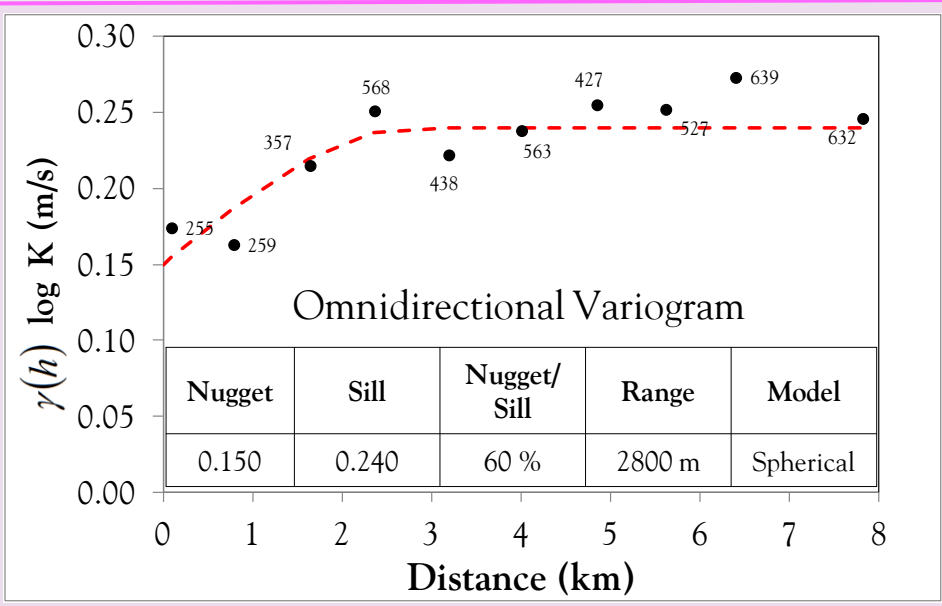
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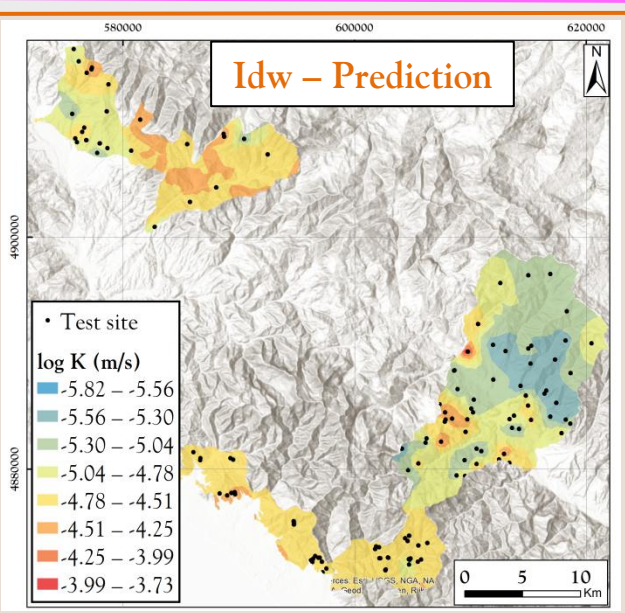
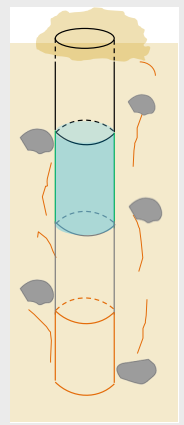


Horizon 2 (20-40 cm) – Ordinary Kriging (O_rK_r) and Inverse Distance Weighting (Idw)

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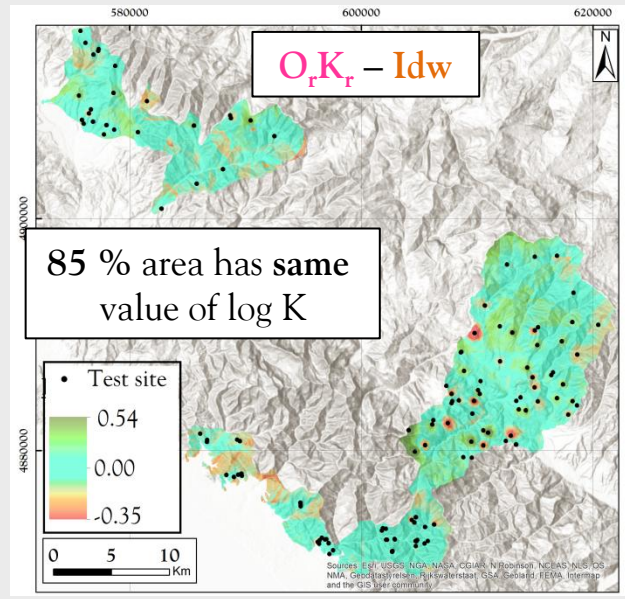
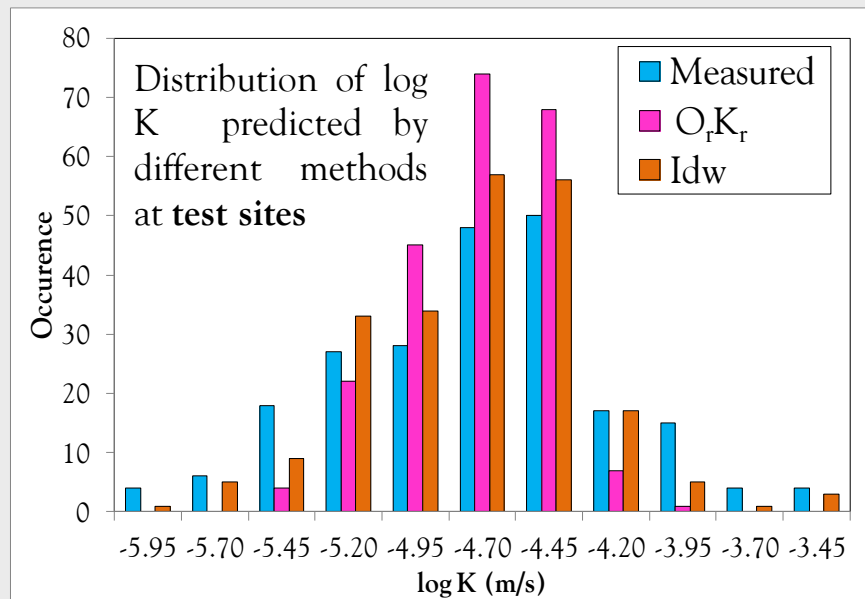
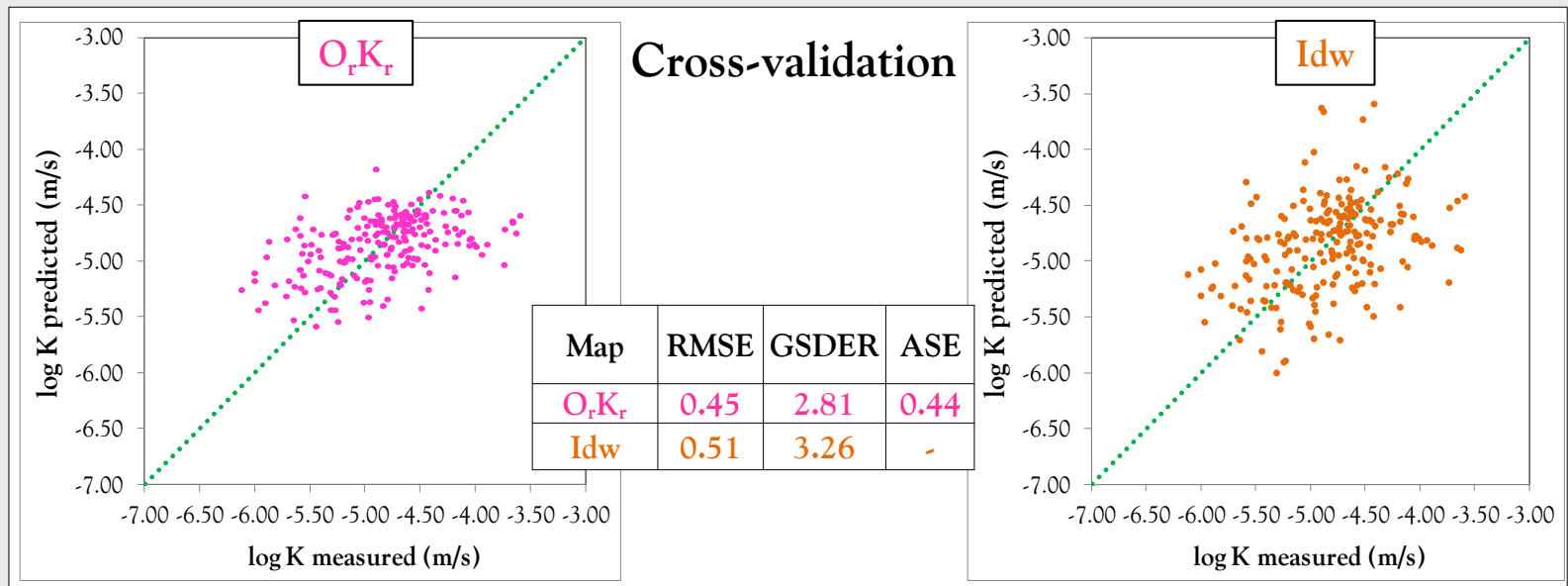
Power	2
Range	3000 m





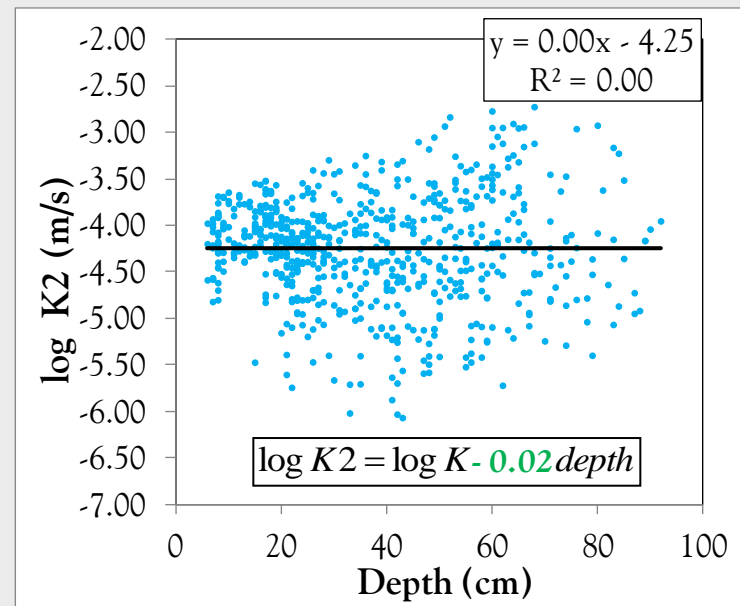
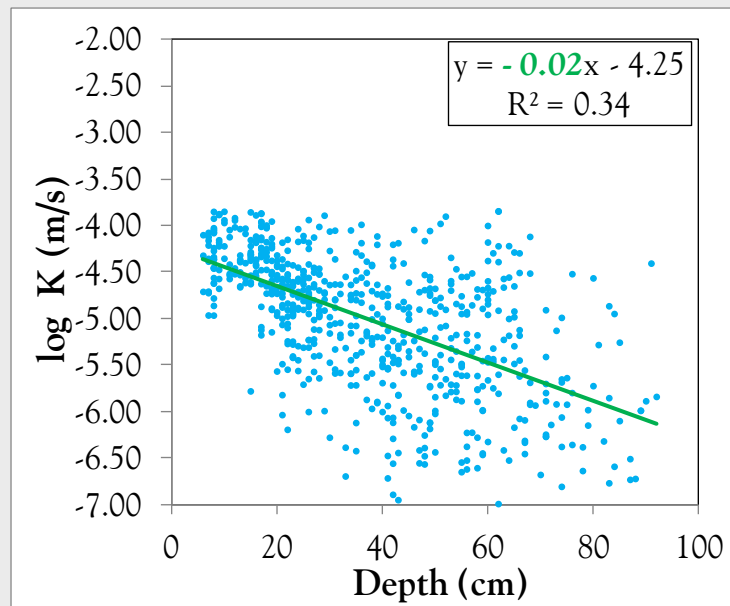
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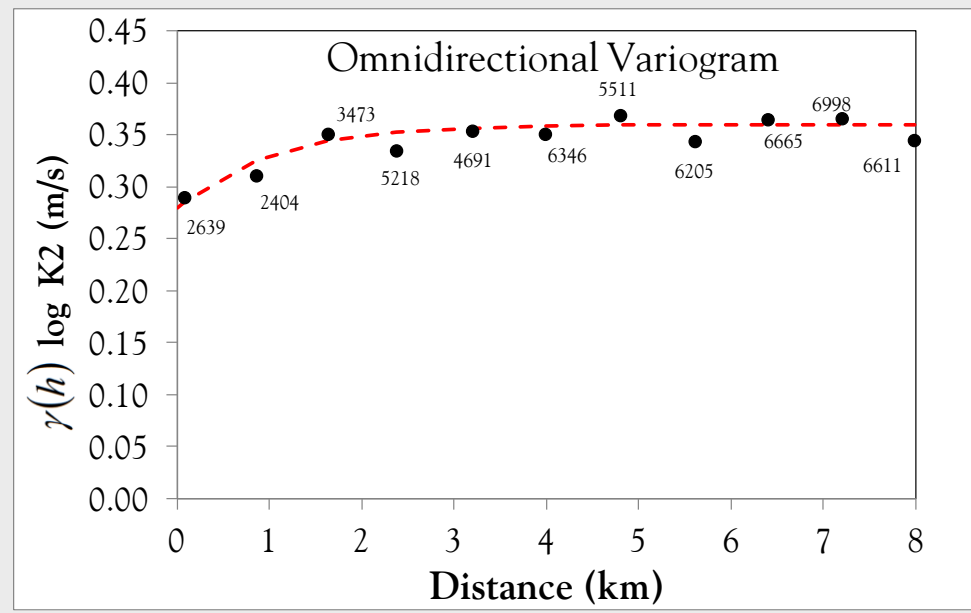


All Ktests – Detrend analysis



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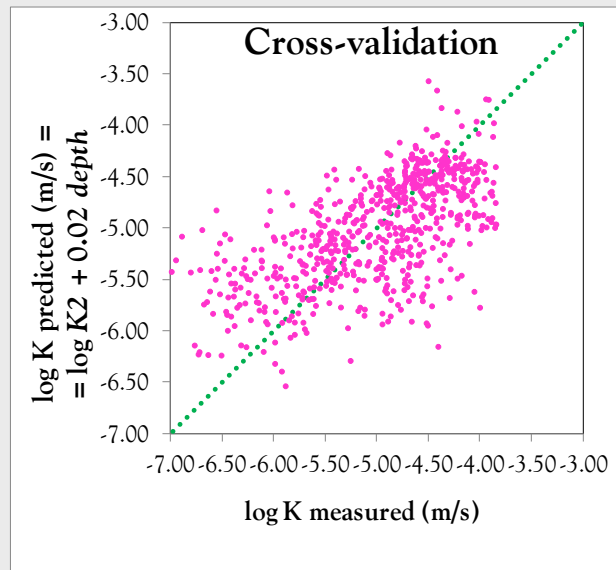
Parameter	log K2
Nugget	0.28
Sill	0.36
Nugget/Sill	80 %
Range	3000 m
Model	Exponential



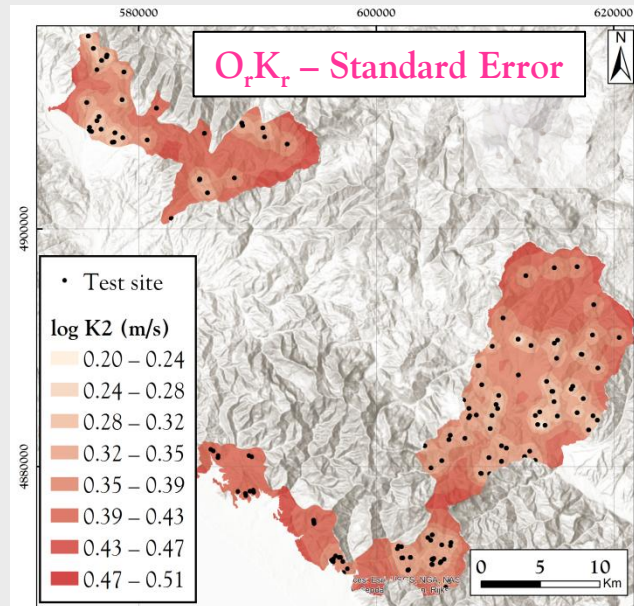
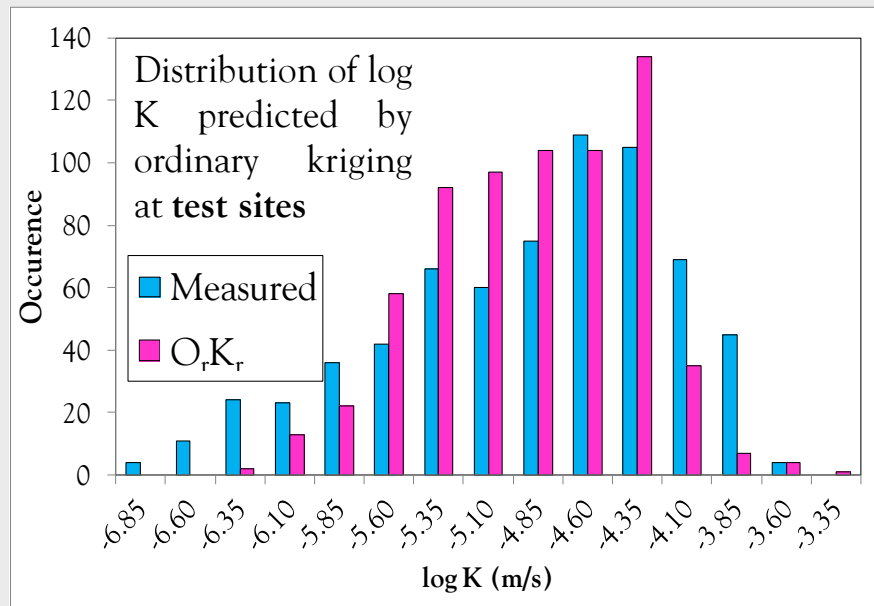
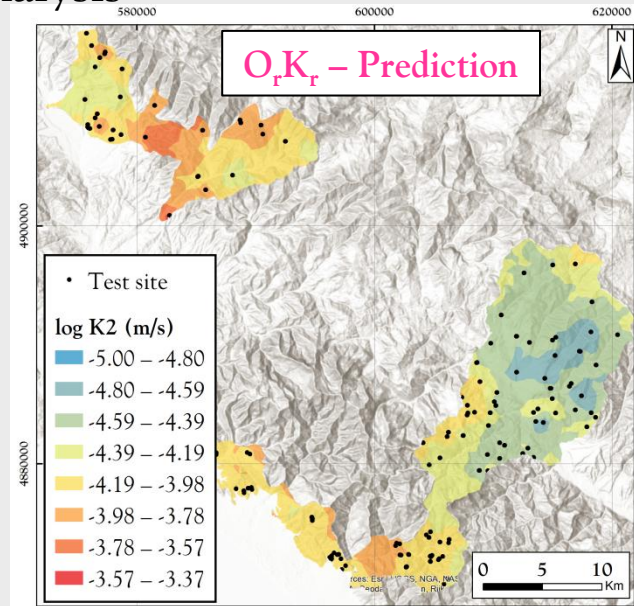


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All Ktests – Detrend analysis



Error	log K (m/s)
RMSE	0.55
GSDER	3.57
ASE	0.48





- ✓ **Texture classes** of slope deposits are mostly muddy gravel (**mG**), muddy sandy gravel (**msG**) and gravelly mud (**gM**). The interquartile range of C_U is $\approx 80-600$
- ✓ **Site variability** of log K in term of **interquartile range** and **range** is respectively **0.8** and **1.9**
- ✓ **Negative trend** of log K with **depth** and **different** distribution of log K among **horizons**
- ✓ Spatial structure of log K in the experimental variogram characterized by an **high nugget/sill**
- ✓ **Geostatistical methods** are implemented to obtain continuous maps of log K:
 - ❑ **Horizons approach: Ordinary Kriging** and **Inverse Distance Weighting** provide maps each other **similar** of log K for the corresponding horizons
 - ❑ **Inverse Distance Weighting** is able to predict **extreme** values of log K
 - ❑ **Detrend approach: Ordinary Kriging** allows to include the effect of depth
- ✓ Following up
 - ❑ Continue geostatistical approach for **horizon 3** and **4**
 - ❑ **Implement other** methods to obtain continuous maps of log K (**Empirical Bayesian Kriging**, etc..) and/or use the **pedotransfer function** (already developed by multilinear regression analysis)
 - ❑ Integrate the role of different geological **substratum** in the spatial analysis of log K

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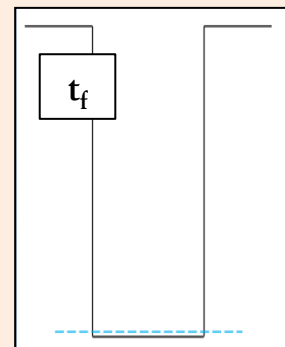
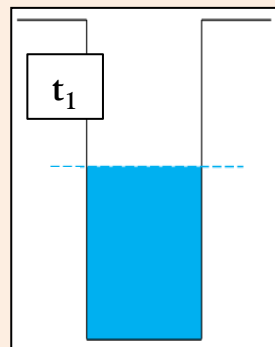
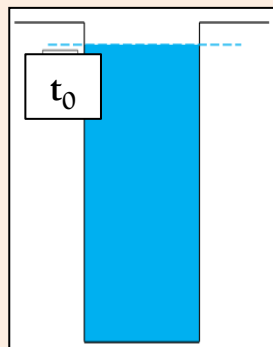
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A scenic landscape featuring a field of purple crocuses in the foreground, with snow-capped mountains in the background. The text "Thank you for attention" is centered in the middle of the image.

Thank you for attention

Field survey: Falling head permeameter



Field survey: Constant head permeameter (Aardvark permeameter)

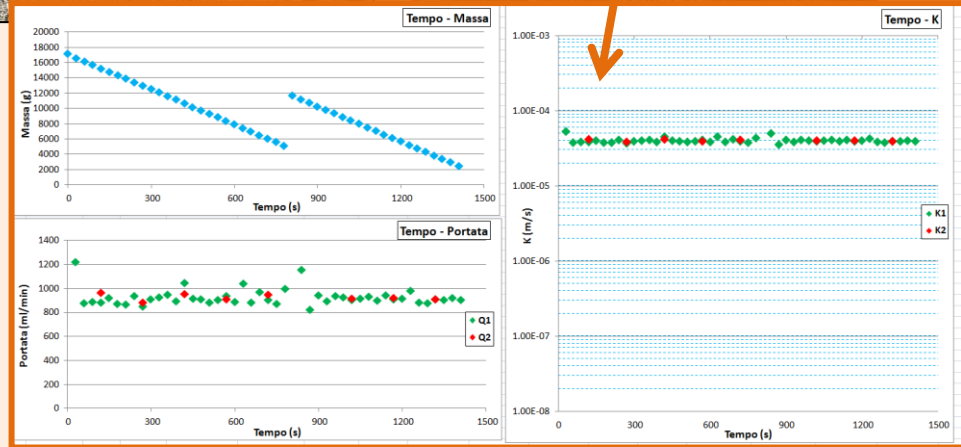
Acquisition and registration equipment

Borehole and permeameter

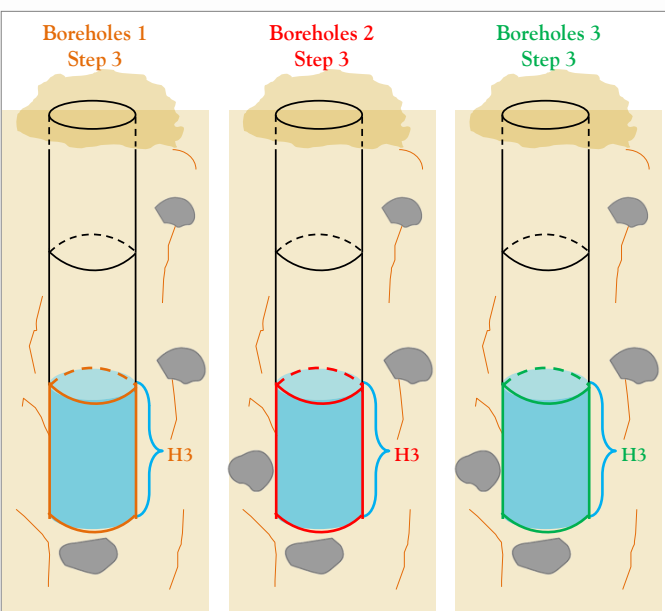
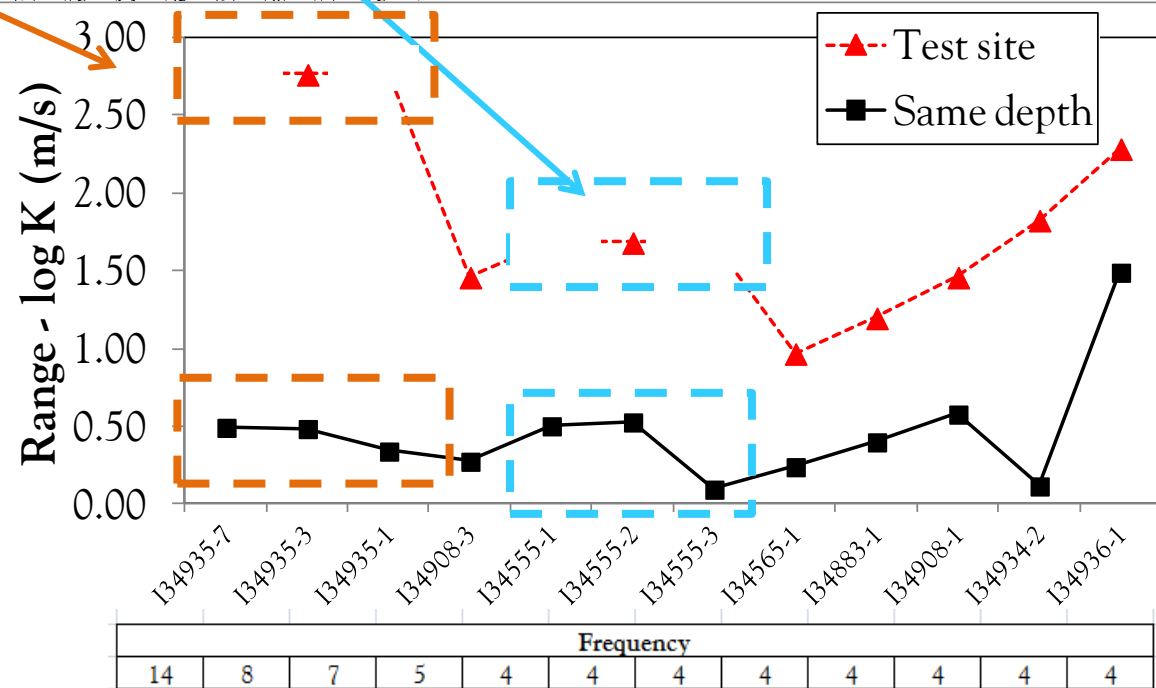
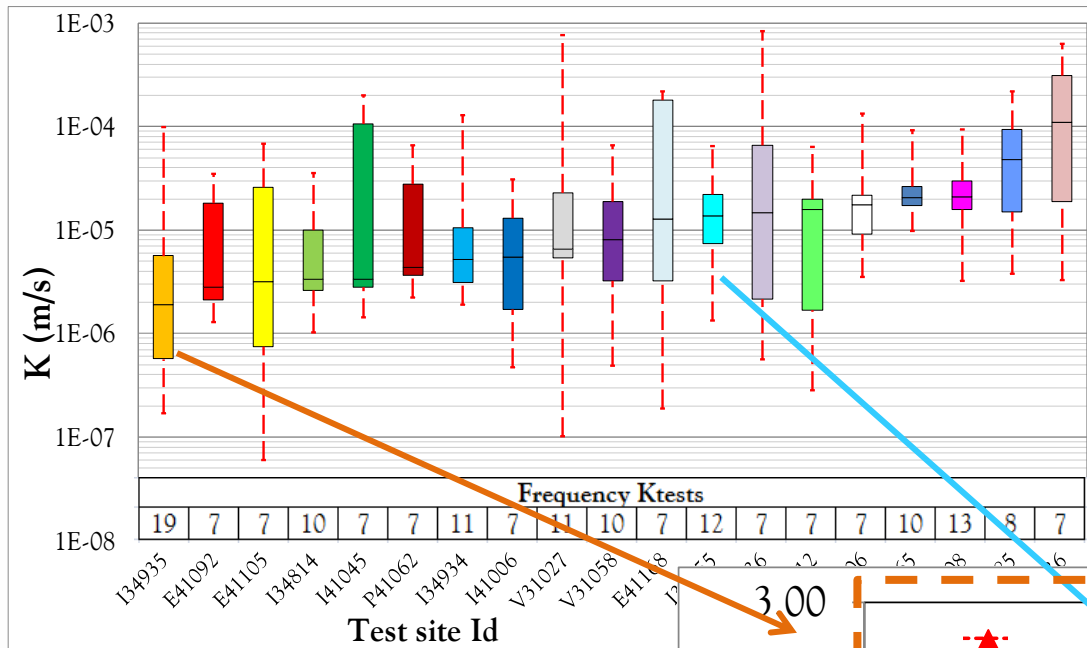
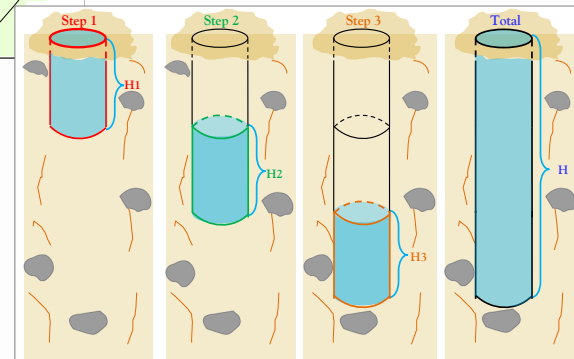
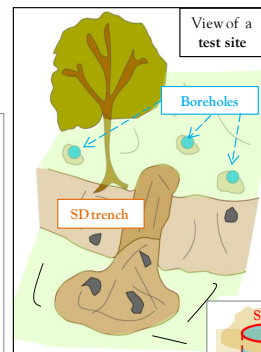
Trench

110 cm

$$t_0 = t_1 = t_f$$



Site variability



Statistical error
equation

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (\log K_P - \log K_M)^2}{n}}$$

K_P = hydraulic conductivity predicted
 K_M = hydraulic conductivity measured

$\overline{K_M}$ = average hydraulic conductivity measured

n = number of data

log = logarithm to the base 10

ln = logarithm to the base e

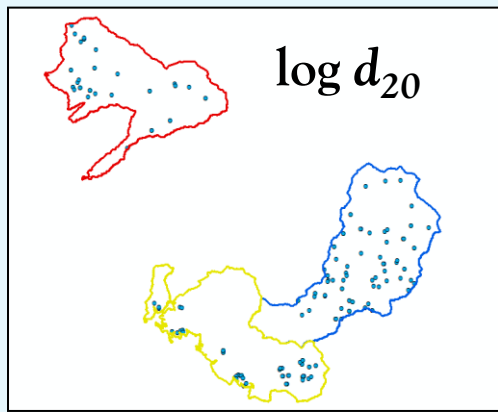
$\sigma_i(x_i)$ = standard error at location x_i

$$GSDER = \text{Exp} \sqrt{\left[\frac{1}{n-1} \sum_{i=1}^n \left(\ln \frac{K_P}{K_M} - \ln GMER \right)^2 \right]}$$

$$GSDER = \text{Exp} \left(\frac{1}{n} \sum_{i=1}^n \ln \frac{K_P}{K_M} \right)$$

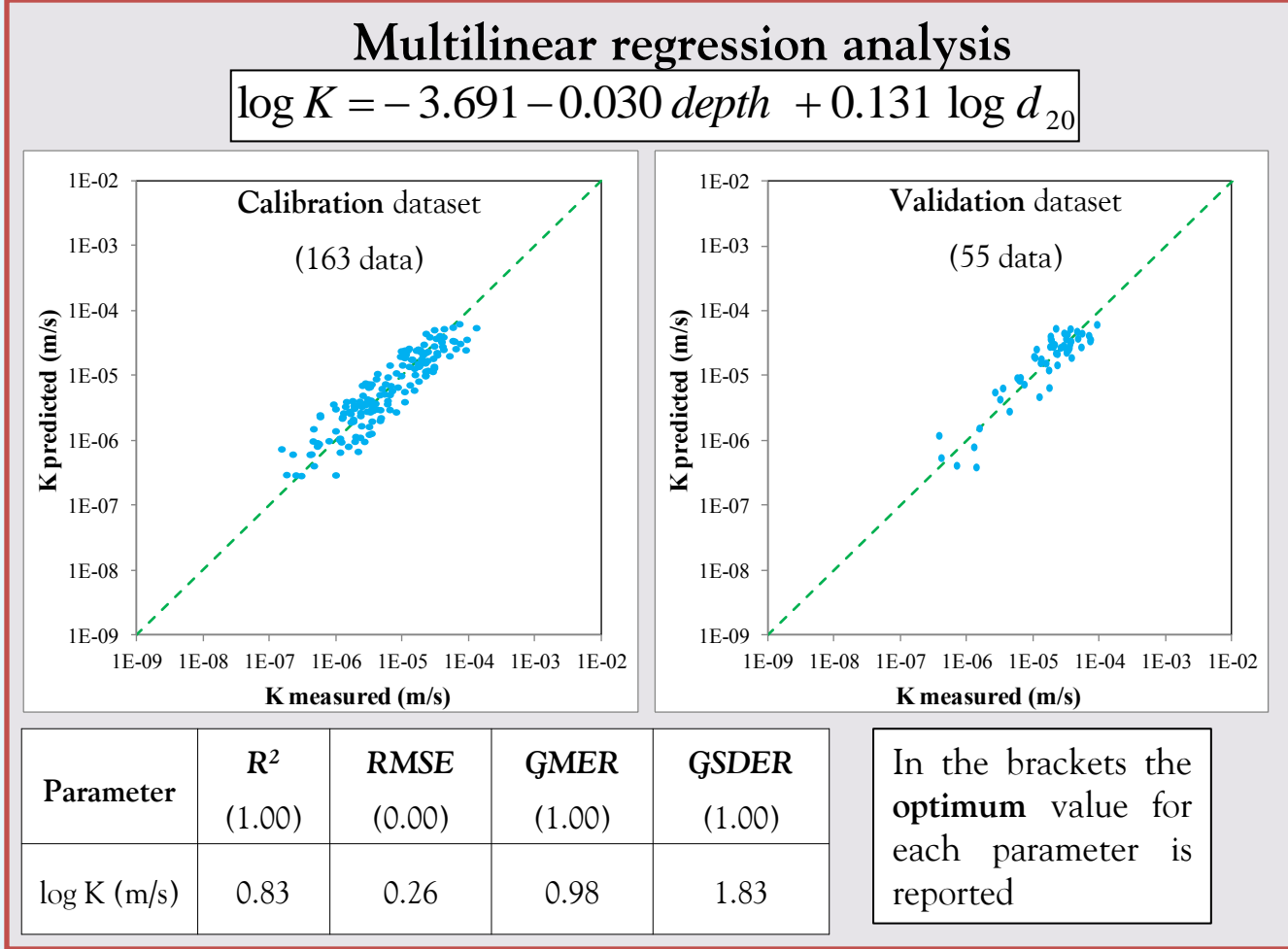
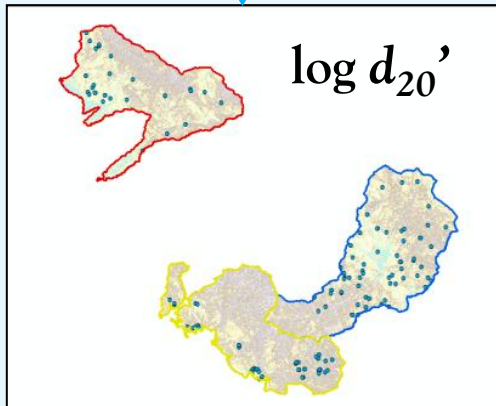
$$ASE = \frac{\sum_{i=1}^n \sigma_i(x_i)}{n}$$

$$R^2 = 1 - \frac{\sum_{i=1}^n (\log K_M - \log K_P)^2}{\sum_{i=1}^n (\log K_M - \log \overline{K_M})^2}$$



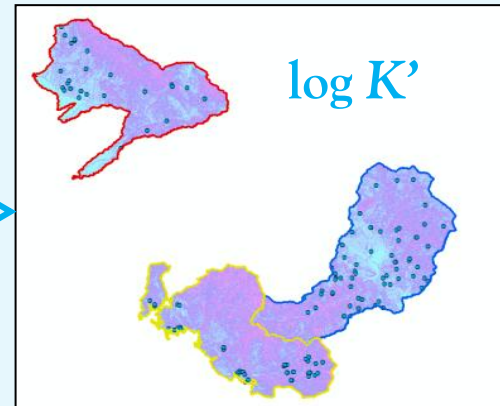
Interpolation

- $O_r K_r$
- Idw
-



$$\log K = -3.691 - 0.030 \text{ depth} + 0.131 \log d_{20}$$

$\log K' = \text{PTF}(\text{depth}, \log d_{20})$
no interpolation is necessary about *depth*



Variograms from literature of log K

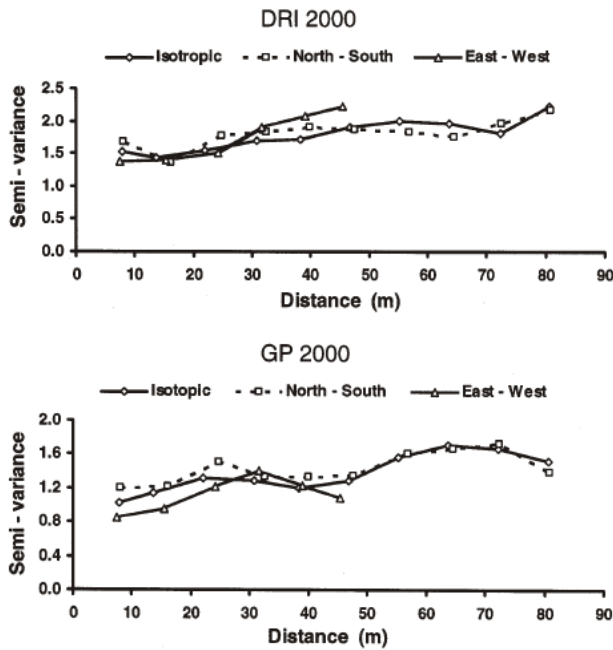


Fig. 6. Empirical variogram of field saturated hydraulic conductivity (K_f) determined by double ring infiltrometer (DPI) and Guelph permeameter (GP).

Variogram of K from Fig. 6 of Gupta *et al.* (2006)

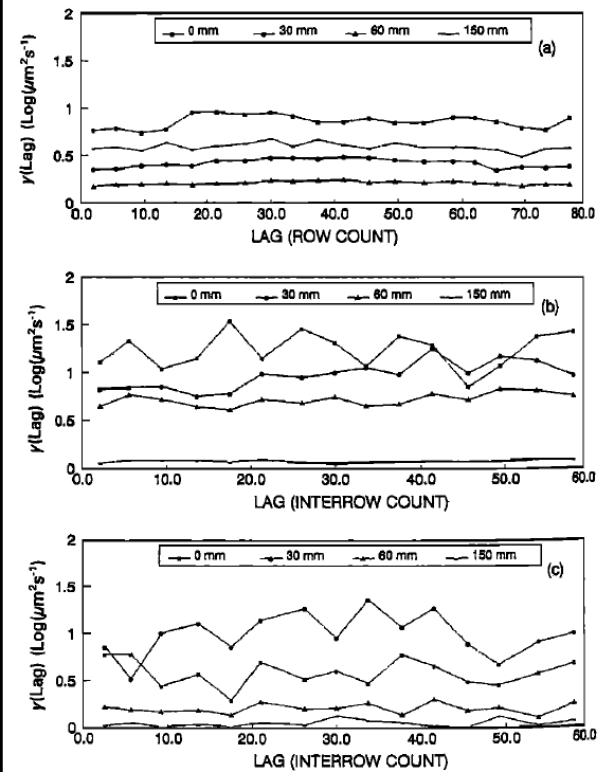


Figure 3. Sample semivariograms of log K with outlier(s) removed under (a) corn row, (b) no-track interrow, and (c) wheel track interrow conditions. (One row or interrow count is 76 cm.)

Variogram of K from Fig.3 of Mohanty *et al* (1994)

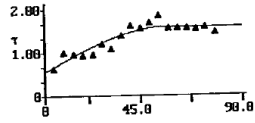
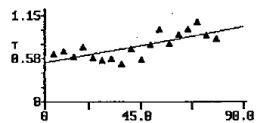
Isotropic Structural Analysis

Depth = 15 cm

Depth = 30 cm

a) $\text{Log}_e K_{15}$ ($\text{Log}_e(\text{cm/hr})$)

b) $\text{Log}_e K_{30}$ ($\text{Log}_e(\text{cm/hr})$)



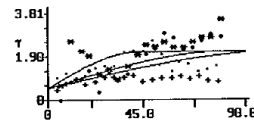
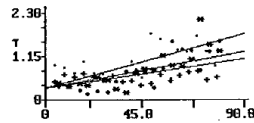
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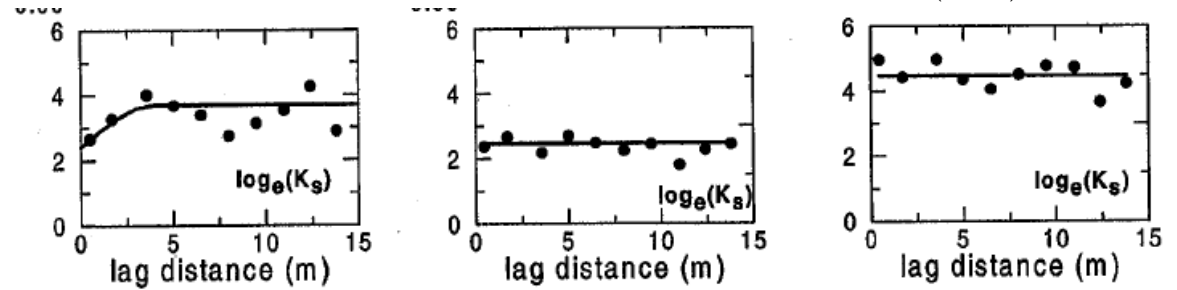
b) $\text{Log}_e K_{30}$ ($\text{Log}_e(\text{cm/hr})$)



Variogram of K from Fig.11, 12 of Mohanty and Mousli (2000)

Variograms from literature of $\log K$

Variogram of K from Fig. 5 of Mallants *et al.* (1996)



Experimental and fitted theoretical semivariogram for hydraulic parameters for the Ap (left), C1 (middle), and C2 (right) horizon. For θ , (C2) both raw (\circ) and detrended data (\bullet) are shown.

Variogram of K from Fig.4 of Sobieraj *et al.* (2002)

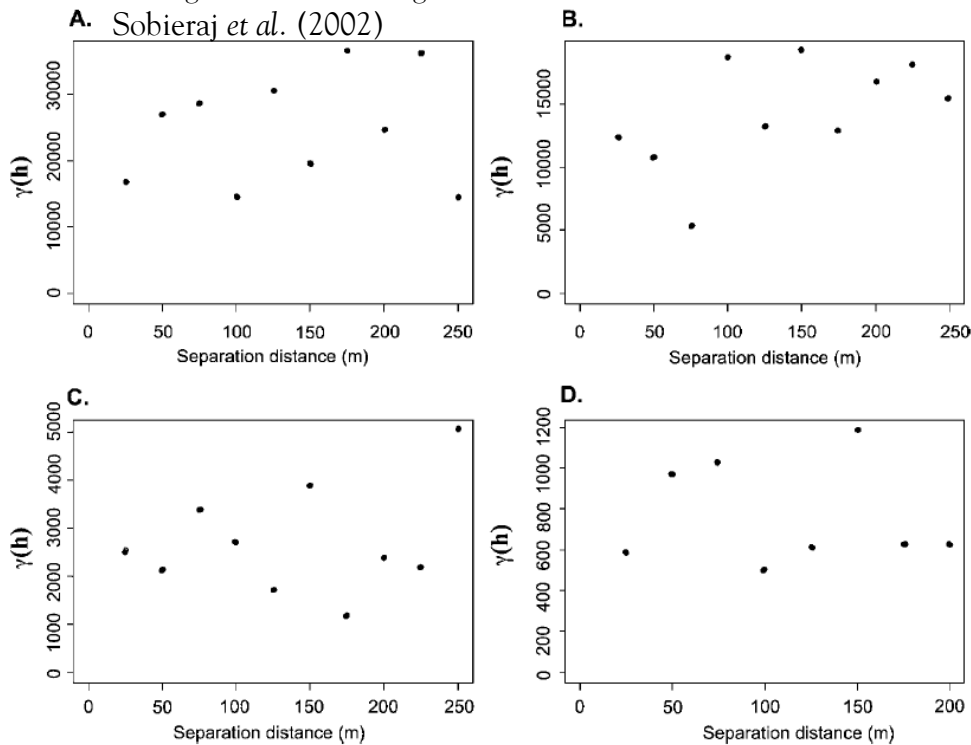


Fig. 4. Empirical semivariograms for K_{sat} data at the following depths (in cm): (A) 20, (B) 30, (C) 50 and (D) 90.