Borehole NMR permeability estimates and uncertainty in an unconsolidated fluvial aquifer, Kansas, USA

Andrew Parsekian, Katherine Dlubac, Jim Butler, Elliot Grunewald, Rosemary Knight and Dave Walsh

Department of Geophysics, Stanford University, Stanford, CA

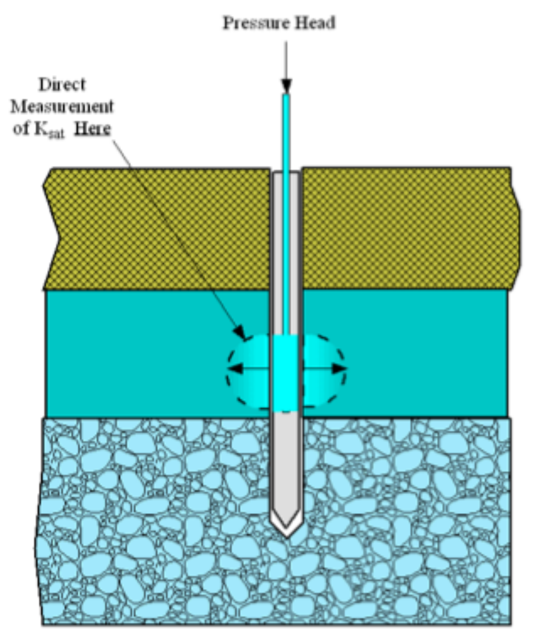
Kansas Geological Survey, Lawrence, KS

Vista Clara Inc., Mukilteo, WA

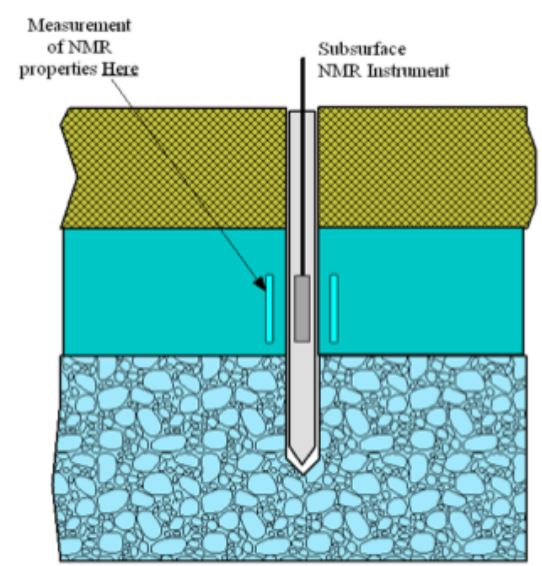
Scientific Relevance

Borehole Nuclear Magnetic Resonance

- Directly sensitive to water
- Porosity estimate
- Permeability estimate
- Often used to evaluate rock formations
- Recent interest in evaluating unconsolidated sediments



Direct push permeameter measures hydraulic conductivity vs. depth.



NMR instrument measures NMR properties as function of depth.

Direct measurements may be used to calibrate NMR estimates

NMR relationship to permeability

$$k_{NMR} = b\phi_{NMR}^{m}(T_{2ML})^{n}$$

"SDR Equation"
T_2= Transverse relaxation time
ϕ= porosity
b = related to the geology/formation (0.1 – 4?)
m= traced to Archies' Law (±4?)
n = describes the scaling between S/V and *k* (2?)

Research Questions

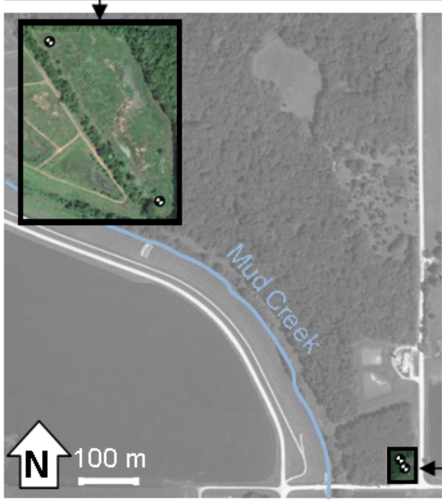
- What parameter values are best for unconsolidated sediments?
- What is the level of uncertainty in the parameters and *k* estimates?
- Is it possible to make calibration measurements in one well and use the parameter values site-wide?

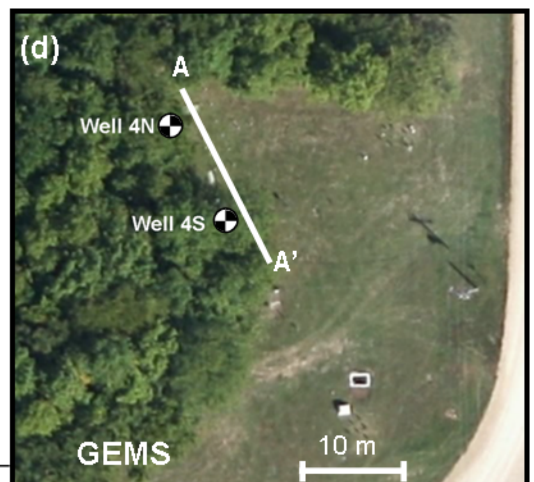
The main point of this talk is…

…to determine acceptable SDR equation parameters to translate NMR T_2 measurements into permeability estimates for unconsolidated sediments.

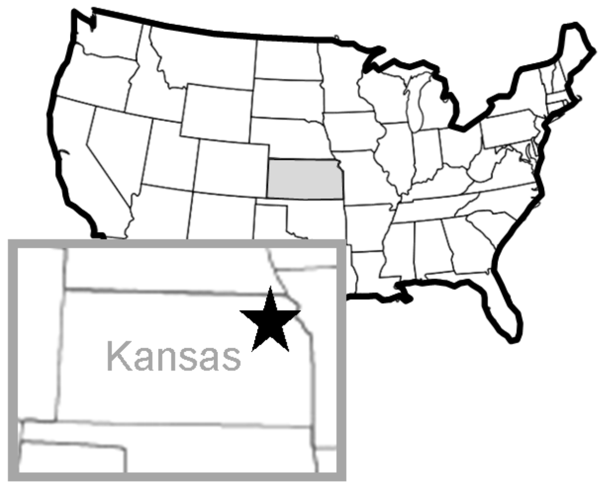
Geohydrological Experiment & Monitoring Site (GEMS)

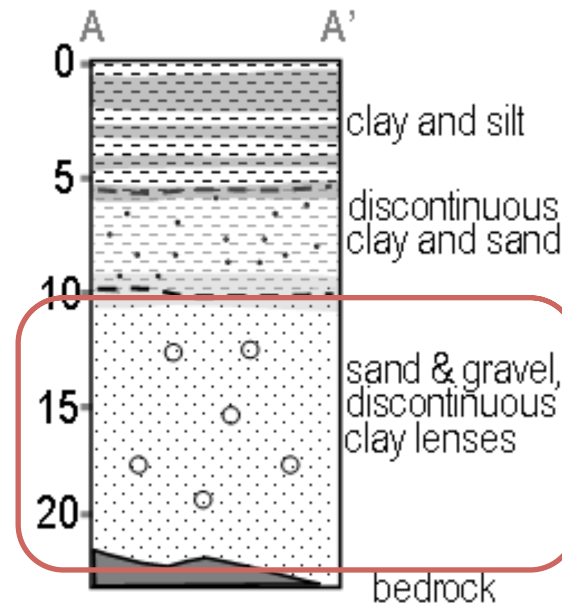
Geoprobe borings used





Existing wells used

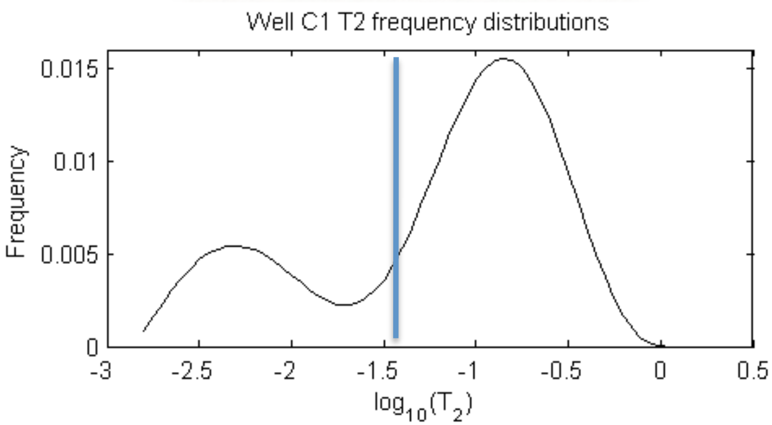




Methods: Field data acquisition

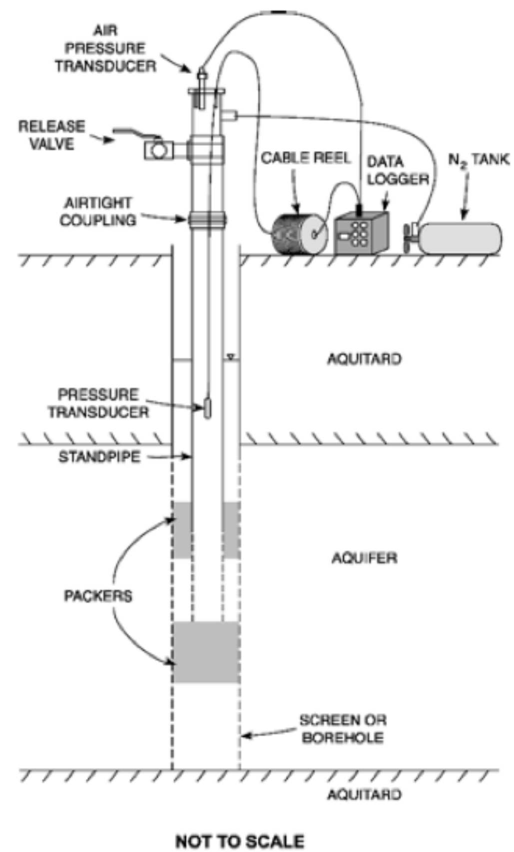
Goal: Make coincident measurements of NMR and permeability

- Javelin Borehole NMR logging (4N, 4S)
- Direct-Push NMR (A1, C1)



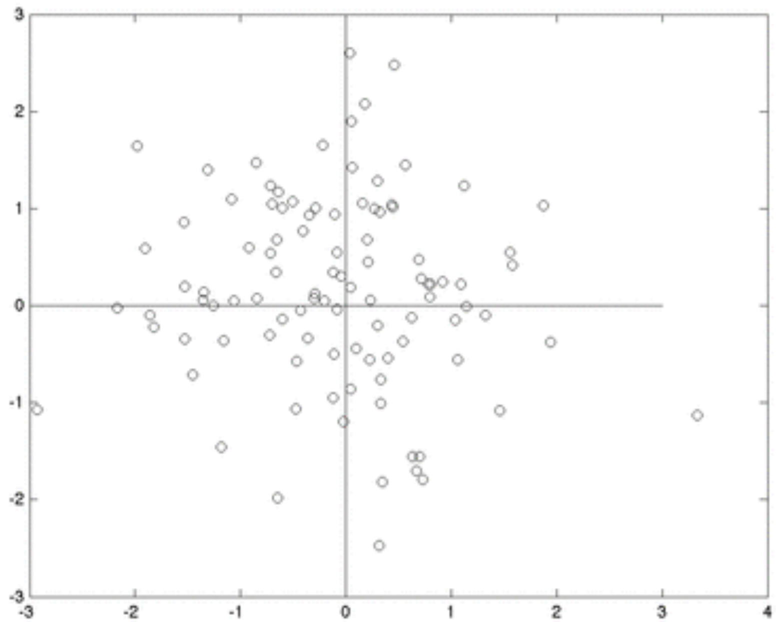
$$T_{2ML} = \exp\left(\frac{\sum \phi_i \log T_{2i}}{\sum \phi_i}\right)$$

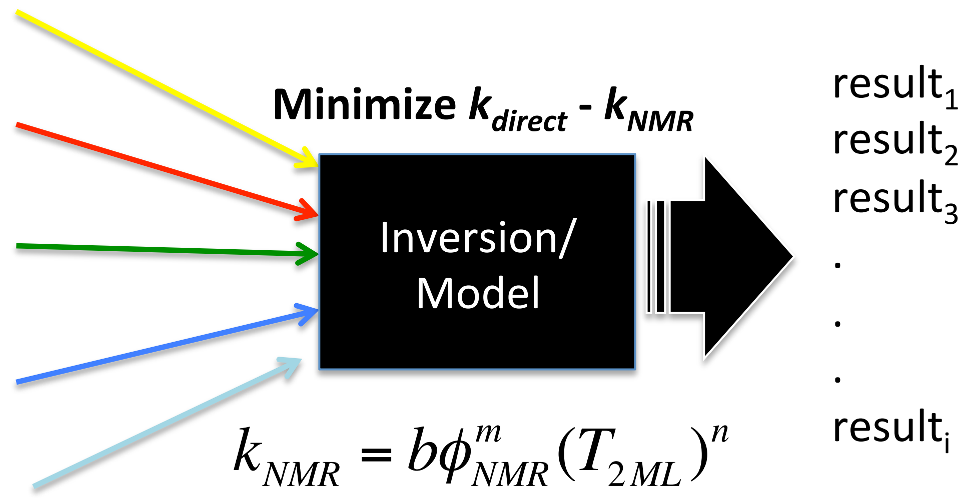
- Multi-level Slug Test (4N, 4S)
- Direct-Push Permeameter (A1, C1)

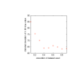


Approach 1: Bootstrapping

Methods: Bootstrapping







Bootstrapping

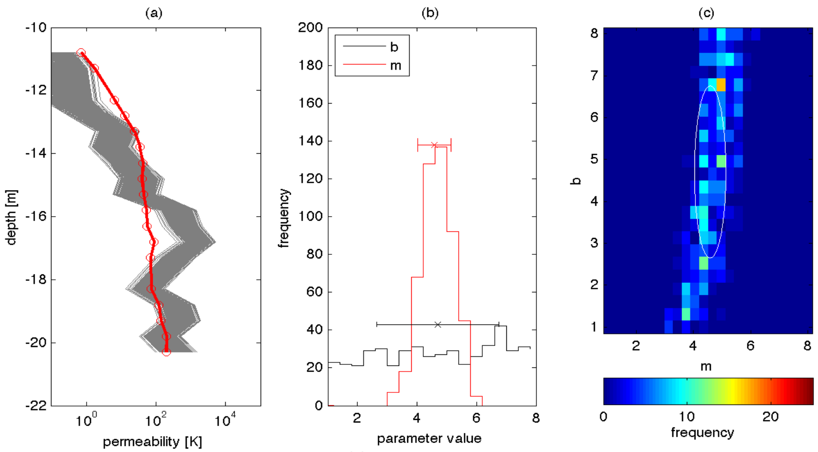
•Optimization for many random subsets of data

•Obtain a distribution of optimized parameter values

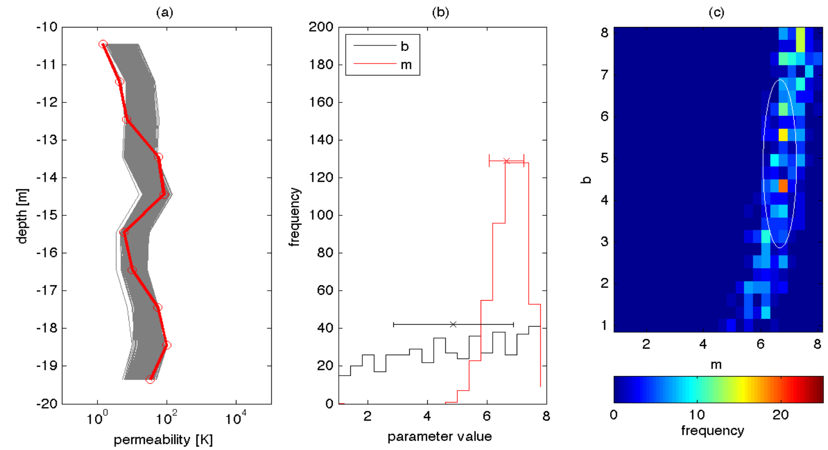
•Results in a range of best-fit permeability models

•Reveals model uncertainty

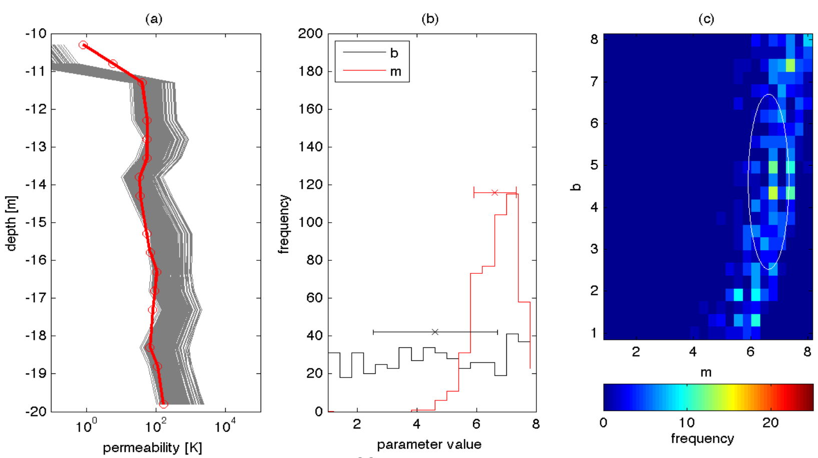
Two-parameter bootstrapping



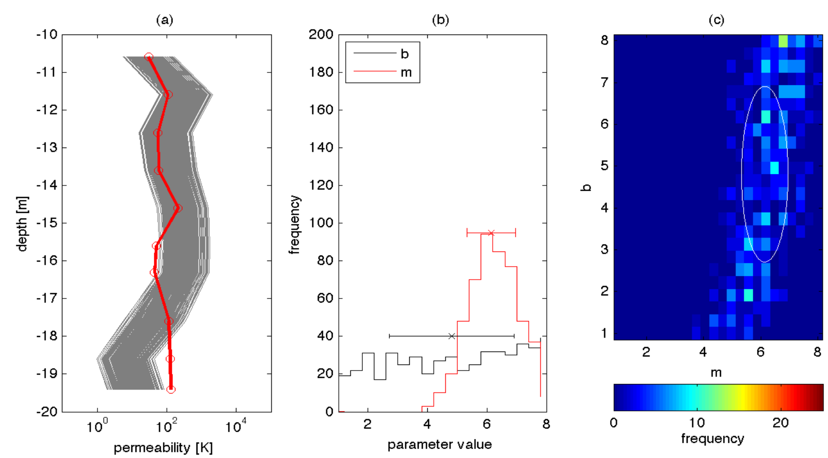
Well 4n



Well A1



Well 4s

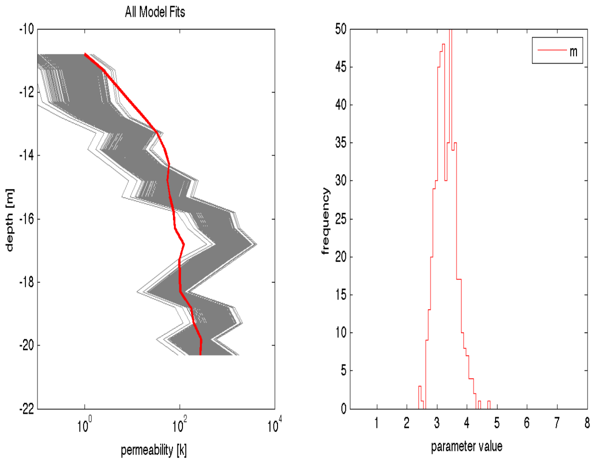


Well C1

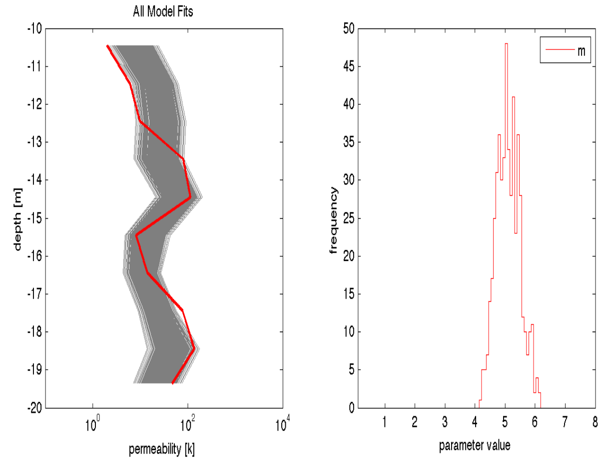
$$k_{NMR} = b\phi_{NMR}^{m}(T_{2ML})^{n}$$

[*n* exponent optimizes to 2]

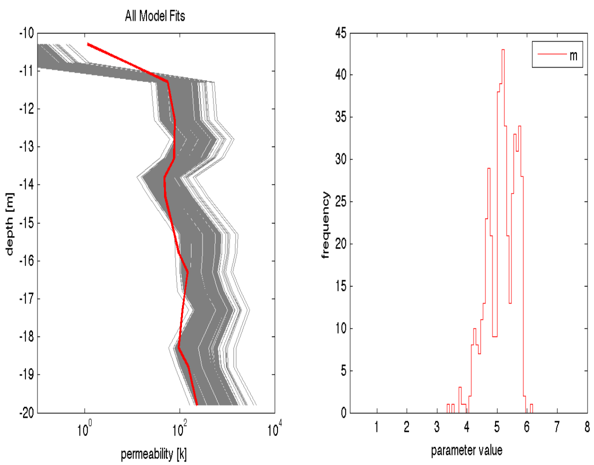
m bootstrap only



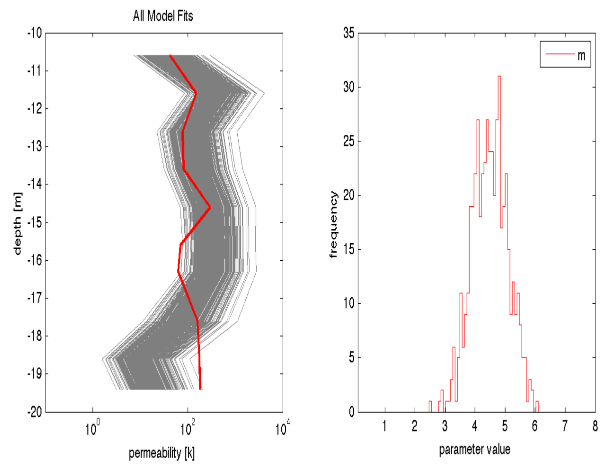
Well 4n



Well A1



Well 4s



Well C1

$$k_{NMR} = b\phi_{NMR}^{m}(T_{2ML})^{n}$$

Parameters estimated by bootstrapping

$$k_{NMR} = b\phi_{NMR}^{m}(T_{2ML})^{n}$$

Well	Mean m	STD m	Mean b	STD b
C1	4.45	0.60	-	-
	6.13	0.82	4.80	2.09
A1	5.04	0.40	-	-
	6.66	0.58	4.87	2.01
4N	3.27	0.35	-	-
	4.58	0.55	4.70	2.05
4S	5.12	0.47	-	-
	6.62	0.71	4.61	2.09

Single Parameter Optimization

Two Parameter Optimization

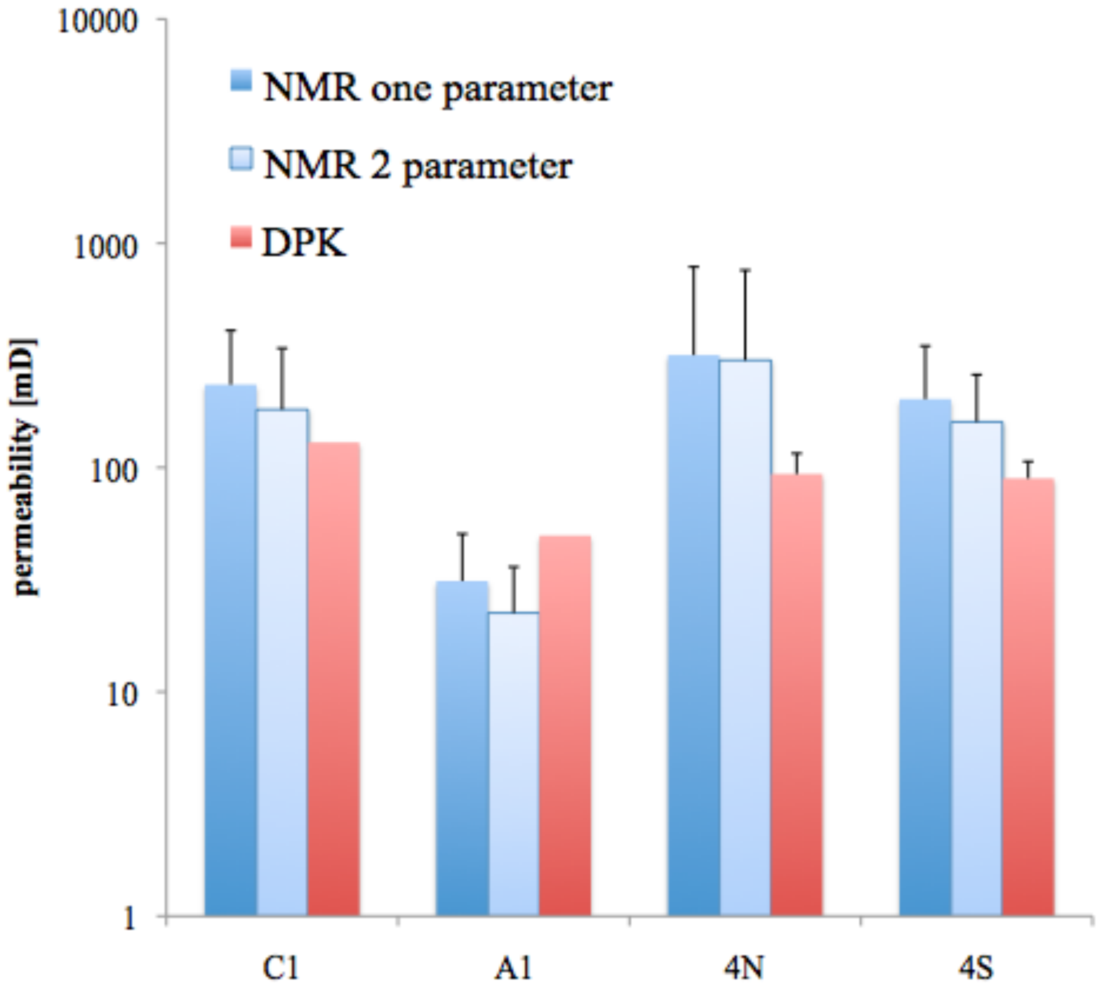
Straley et al. 1997

$$k_{NMR} = \boxed{4.6}\phi_{NMR}^{\boxed{4}}(T_{2ML})^{2}$$

" Traditional" sandstone values

$$k_{NMR} = \boxed{4}\phi_{NMR}^{\boxed{4}}(T_{2ML})^{2}$$

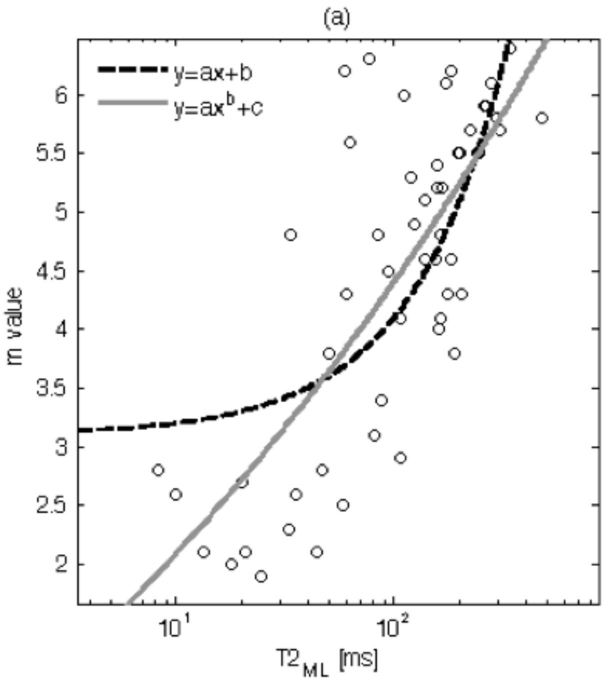
Effect on *k* estimates



Permeability determined using SDR parameters obtained through bootstrapping.

Approach 2: Parameter Prediction

Variable *m* parameter

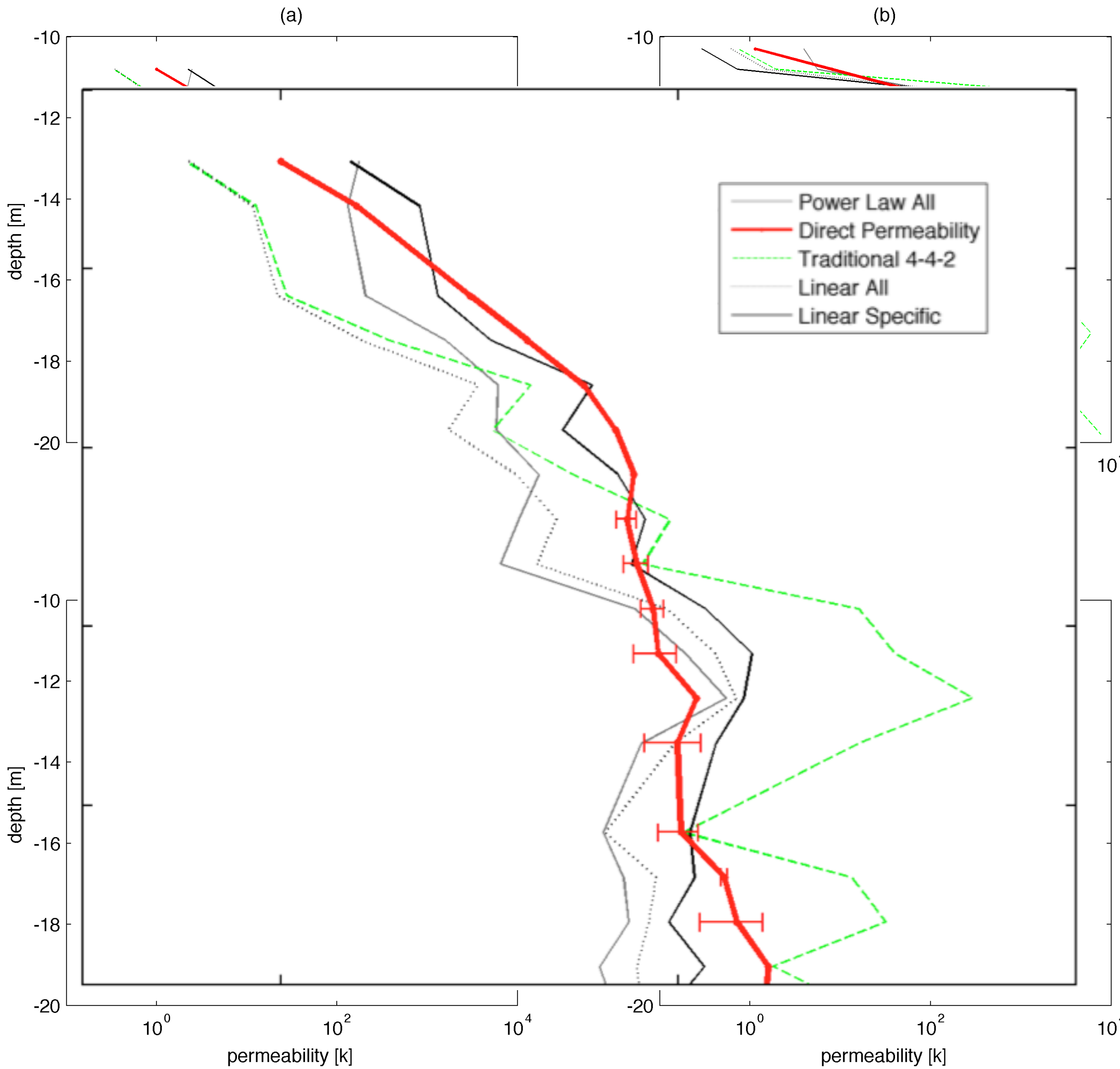


Find the *m* value that lets k_{NMR} equal k_{direct} for each data point pair.

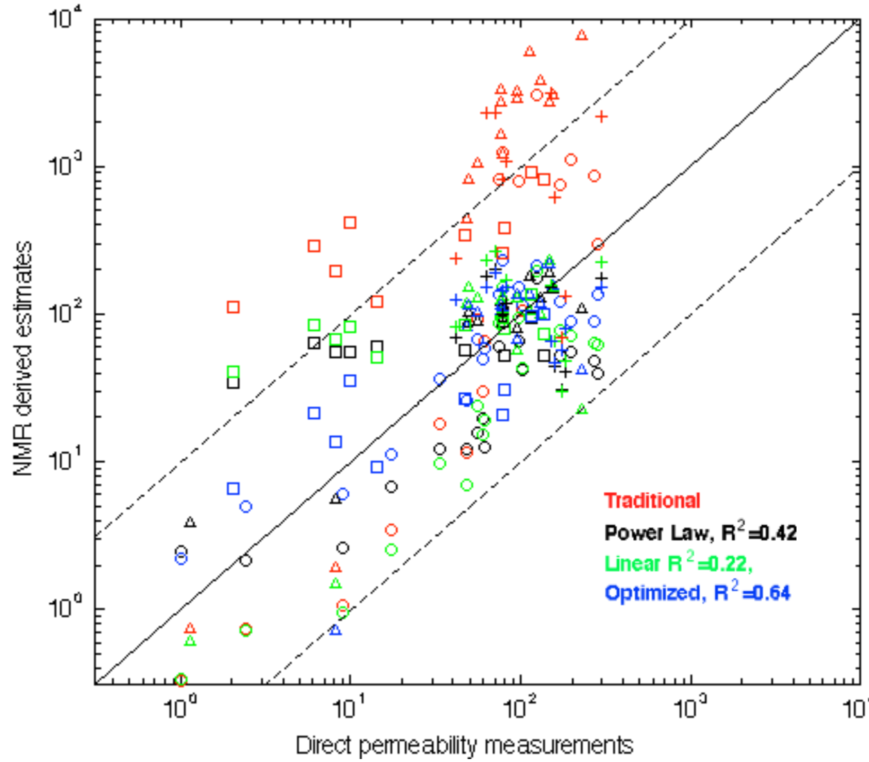
$$k_{NMR} = b\phi_{NMR}^{m}(T_{2ML})^{n}$$

$m=a(T_{2ML})+b$	a	b	c	R^2	p
Well 4N	0.014	2.005	-	0.82	<0.001
Well 4S	0.008	3.626	-	0.63	<0.001
Well C1	0.017	2.264	-	0.61	0.008
Well A1	-0.005	5.490	-	0.06	0.495
all	0.010	3.104	-	0.50	<0.001
$m=a(T_{2ML})^b+c$					
all	5.276	0.124	-4.928	0.57	<0.001

Variable *m* parameter



Variable *m* parameter

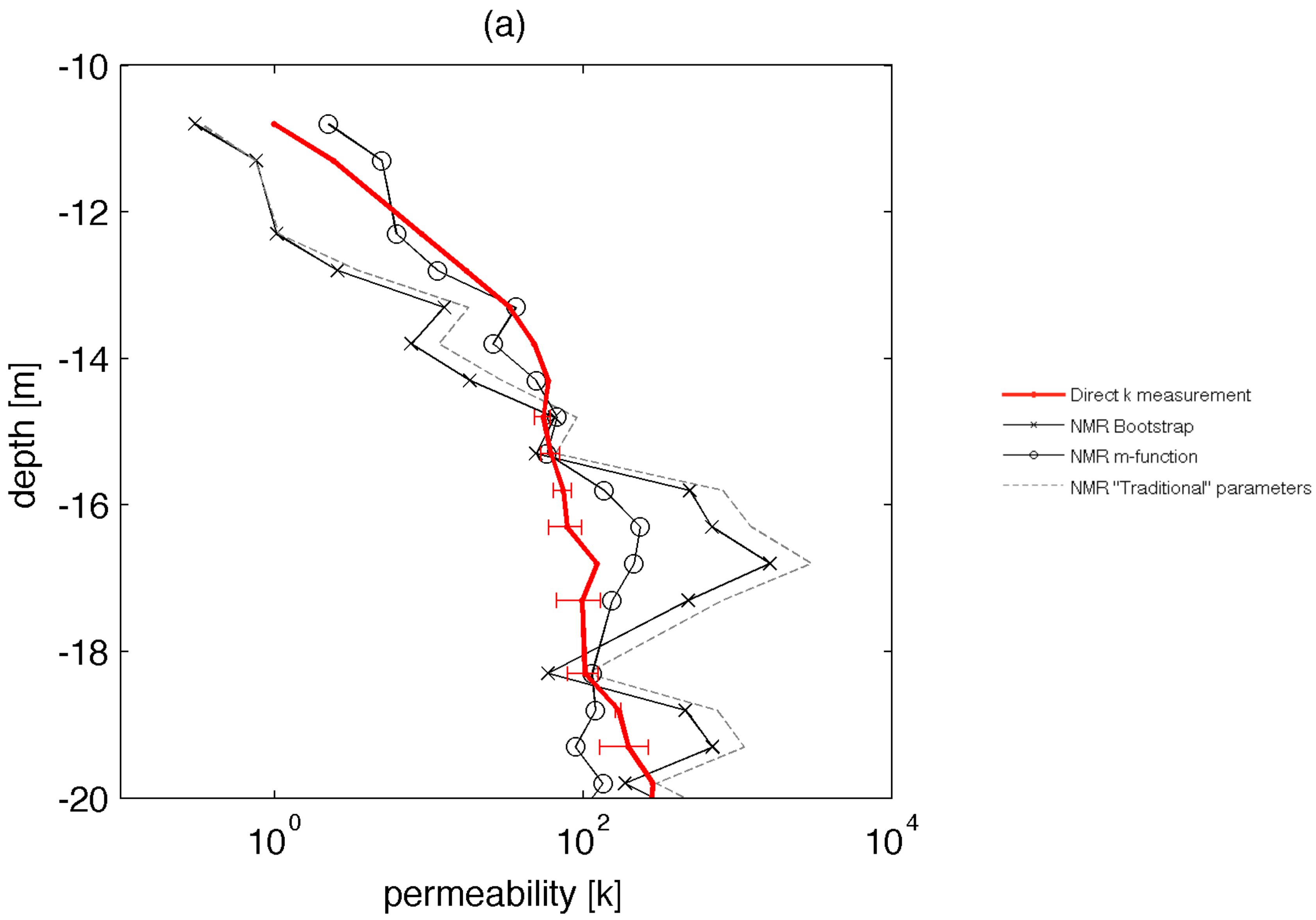


Deviation from 1:1

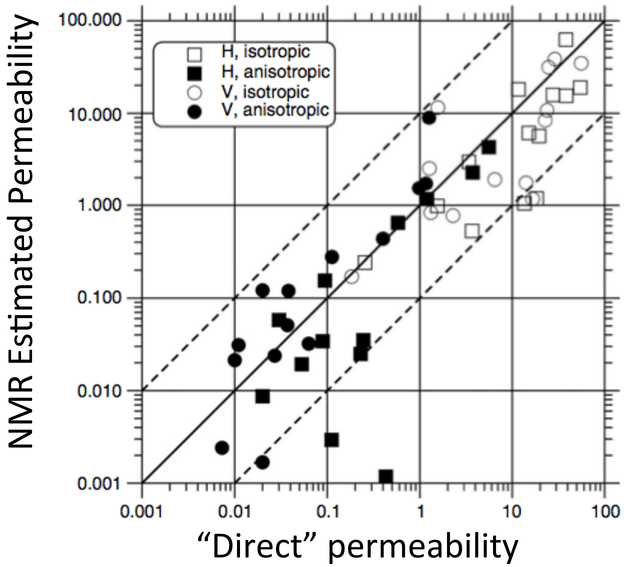
	$k=4\phi^4(T_{2ML})^2$	$k=\phi^{linear}(T_{2ML})^2$ all data	$k=\phi^{power}(T_{2ML})^2$	$k=\phi^{linear}(T_{2ML})^2$ Well 4N	Well 4S	Well C1	Well A1
Well 4S	0.58	0.48	0.43	**0.22**	0.66	0.32	1.17
Well 4N	1.27	0.29	0.18	0.38	**0.28**	0.49	0.85
Well C1	0.93	0.39	0.36	0.38	0.39	**0.38**	0.59
Well A1	1.11	0.55	0.53	0.85	0.47	0.69	**0.35**

Comparison & Discussion

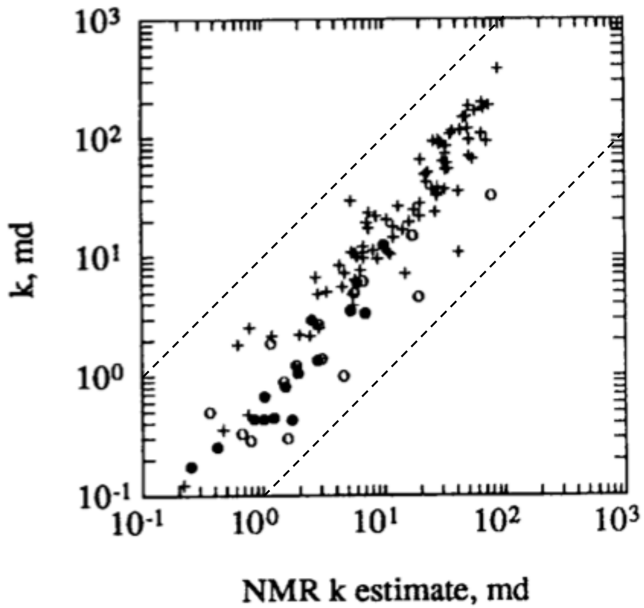
Bootstrapping vs. variable *m*



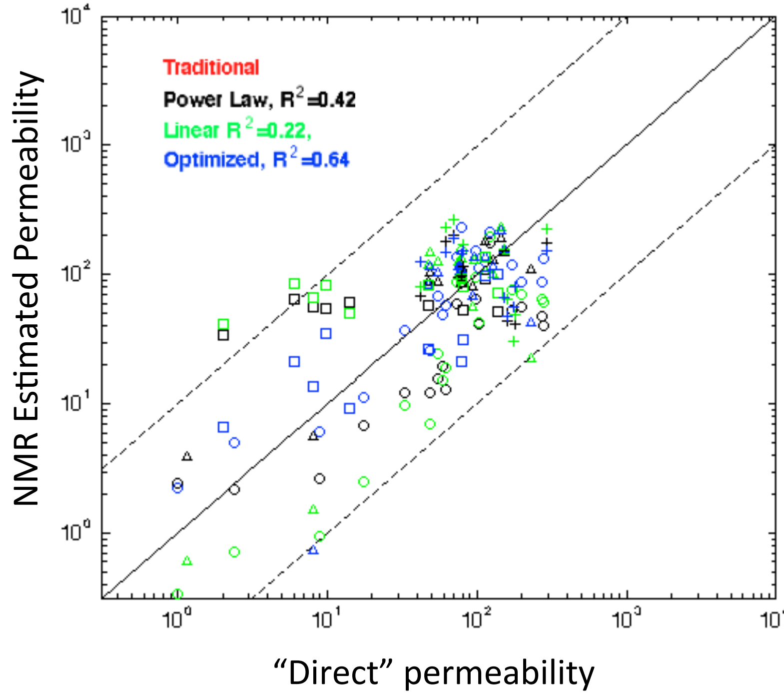
Comparison with previous results



Weller et al., 2010



Straley et al., 1997



Conclusions

- Bootstrapping demonstrates uncertainty when estimating *k* using fixed set of optimized parameters
- Predicting *m* based on T_{2ML} improves the *k* estimate with no additional information
- Site wide calibration may be possible using direct *k* data from one borehole

Thank you for your attention!

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