Discovery & Investigation of Negative Aging (-a) of Foundation Sands under NASA Crawlerways

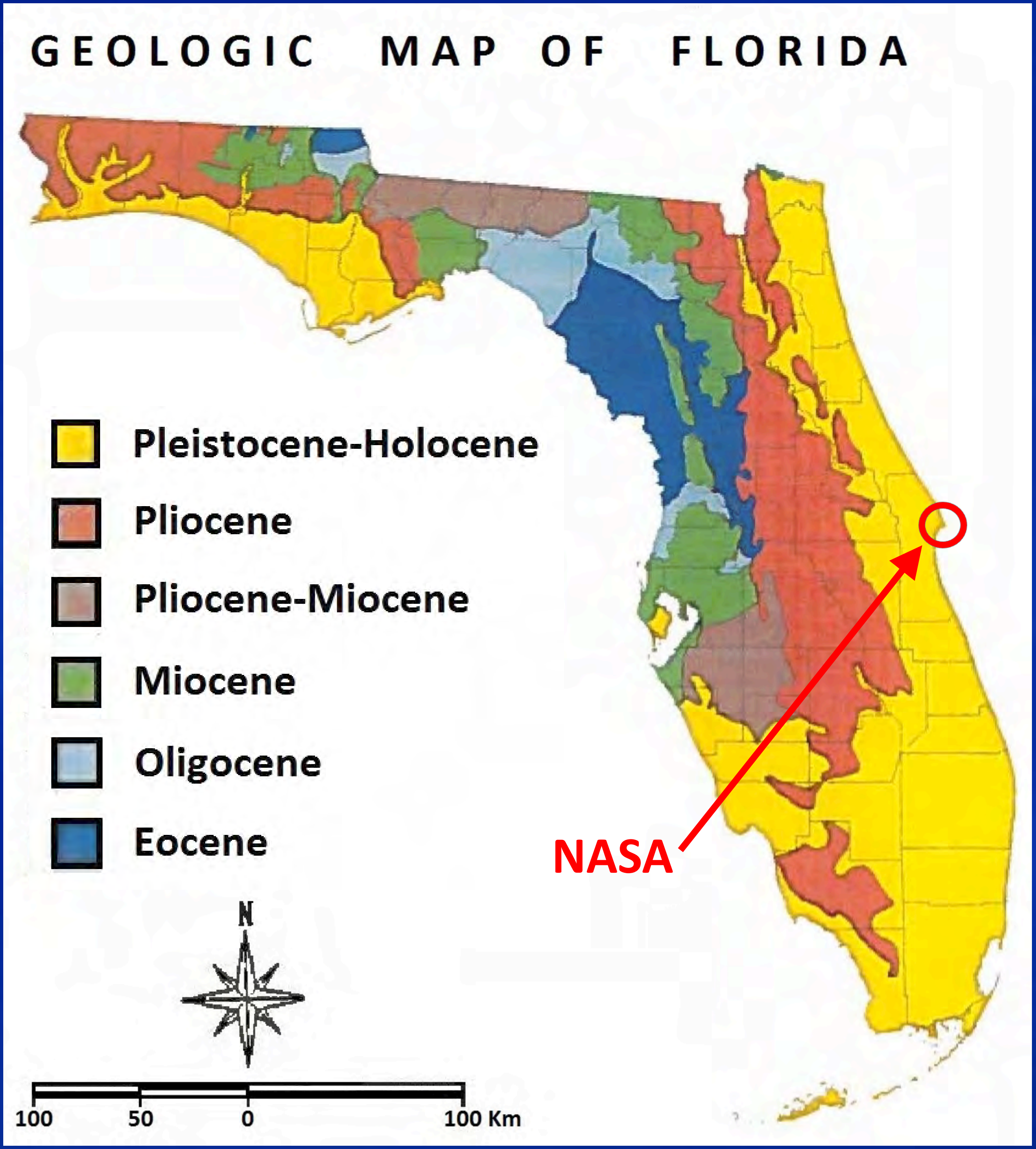
Geo Virginia
Sept. 2019

by John H. Schmertmann

Outline

- Introduction
  - 1963-2008
- CPT Discovery of Negative Aging
  - Examples, 2016-2017
  - (Loads ↑/ Resistance ↓)
- Hypotheses for cause
- Pro and Con Evidence
  - hA – Residual Creep
  - hB – D Solution of shell
- Comments and Next Phase
  - Reliability

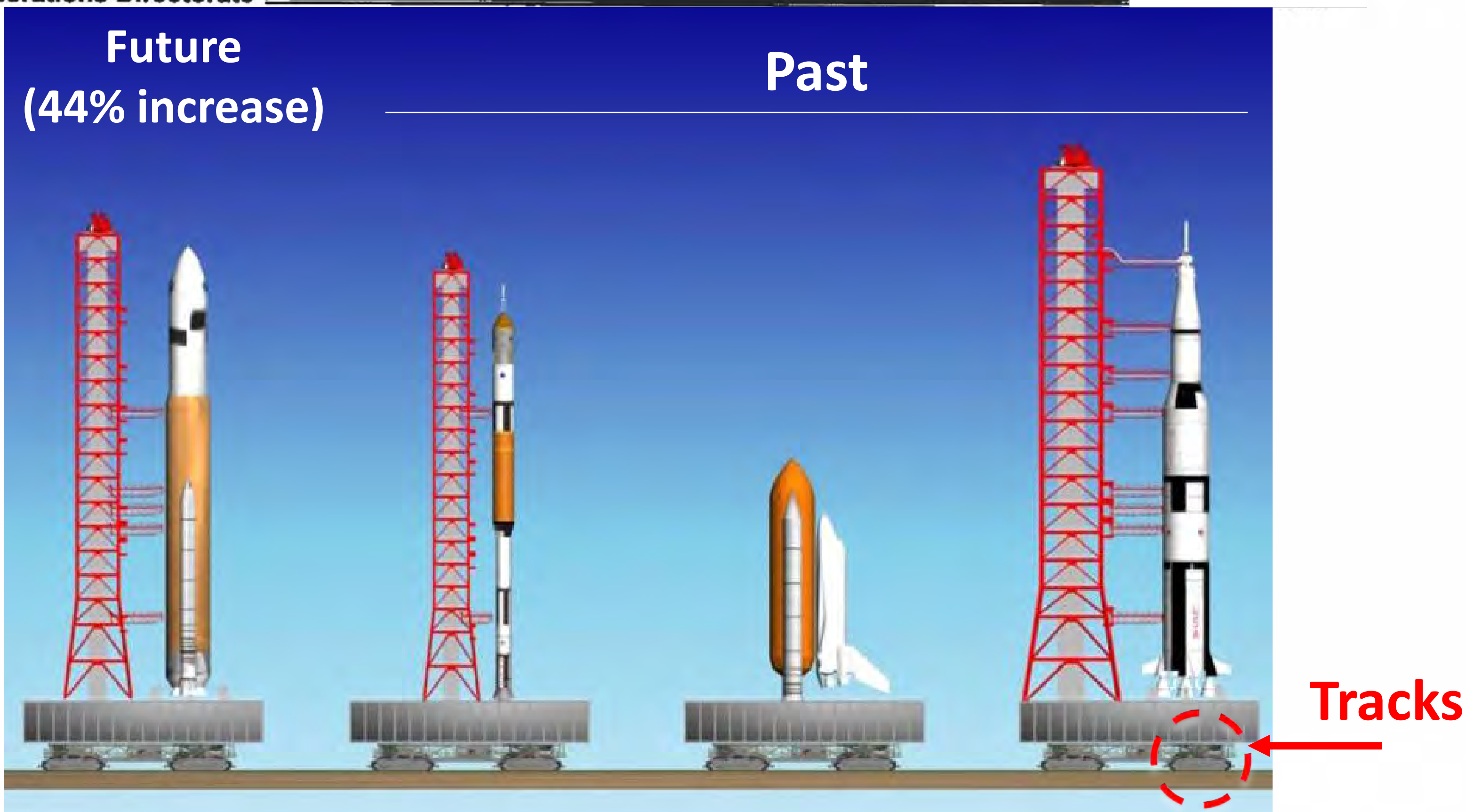
INTRODUCTION



Transporter with Shuttle on Crawlerway A

Heavy Transporter Loads on Crawlerways A and B

Kennedy Space
Center Operations Directorate



2020+ Mars	2010 Ares I	2008 Shuttle	1960s Apollo
26 million lbs	**<18**	**18**	**18**

CWA Under Construction (Feb 1964)

2.3×10^6 m^3 of hydraulic fill

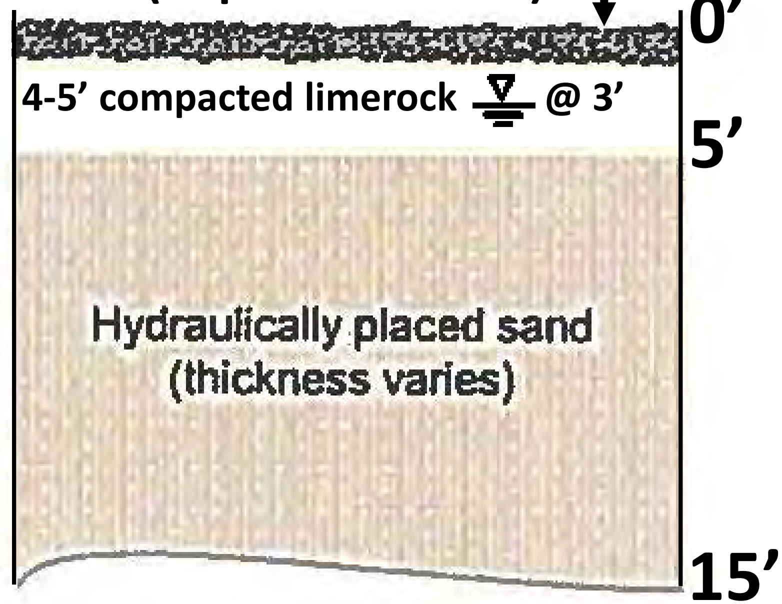
Vibratory and 100 ton rollers compacted roadways

2.3m above sea level (7.5 ft)

Kennedy Space Center
Center Operations Directorate
Facilities Division

Crawlerway History & Section

River-run gravel (6-8 inches)
(imported 500 mi)

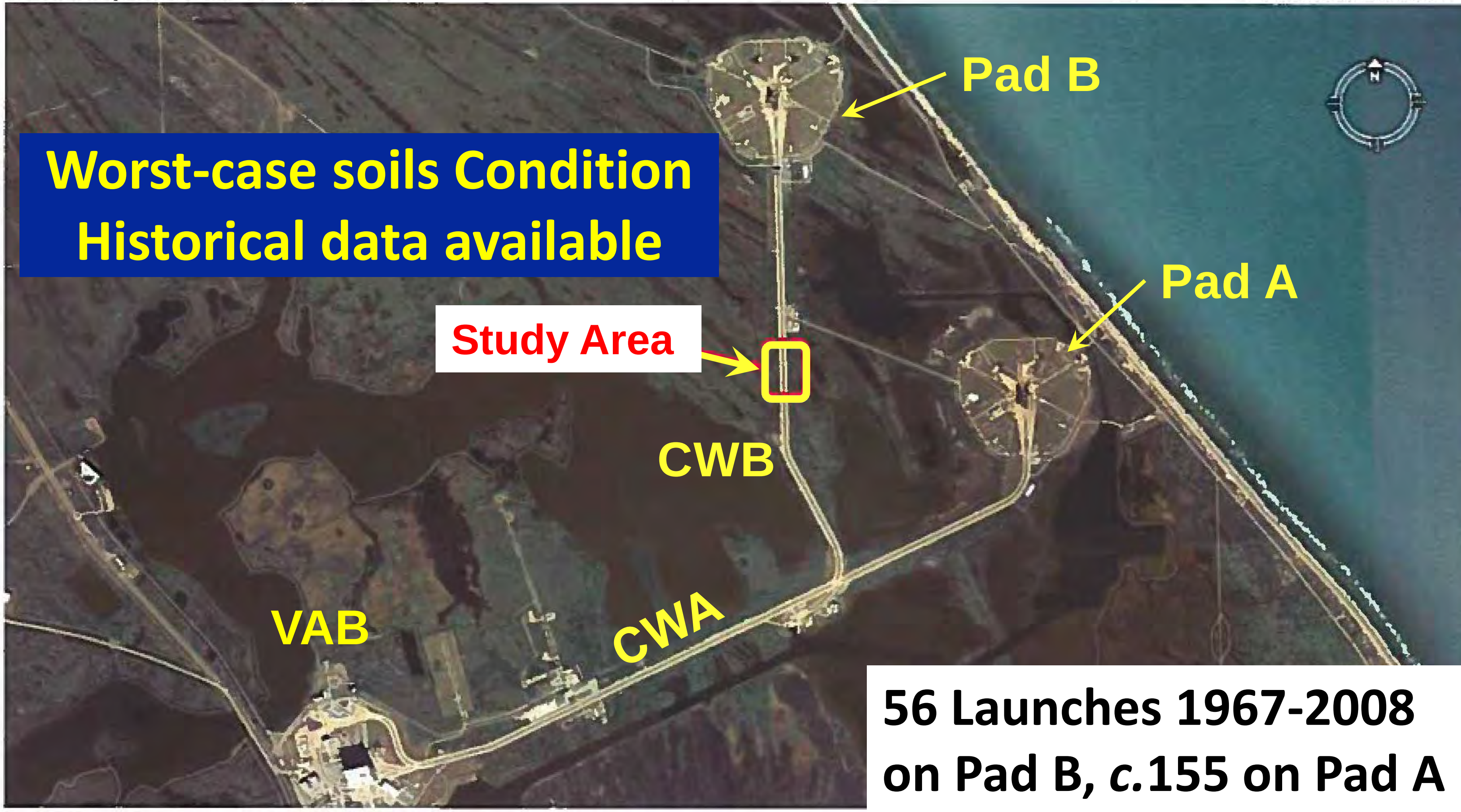


- 1963 to 1966
- 5.6-miles long (approx. 9km)
- Constructed through Lagoon System

Natural sands and silts with shell

Peck's 1967 Observation & Phase 1 Study Area

Crawlerway B, Station 49+00 to Station 55+00

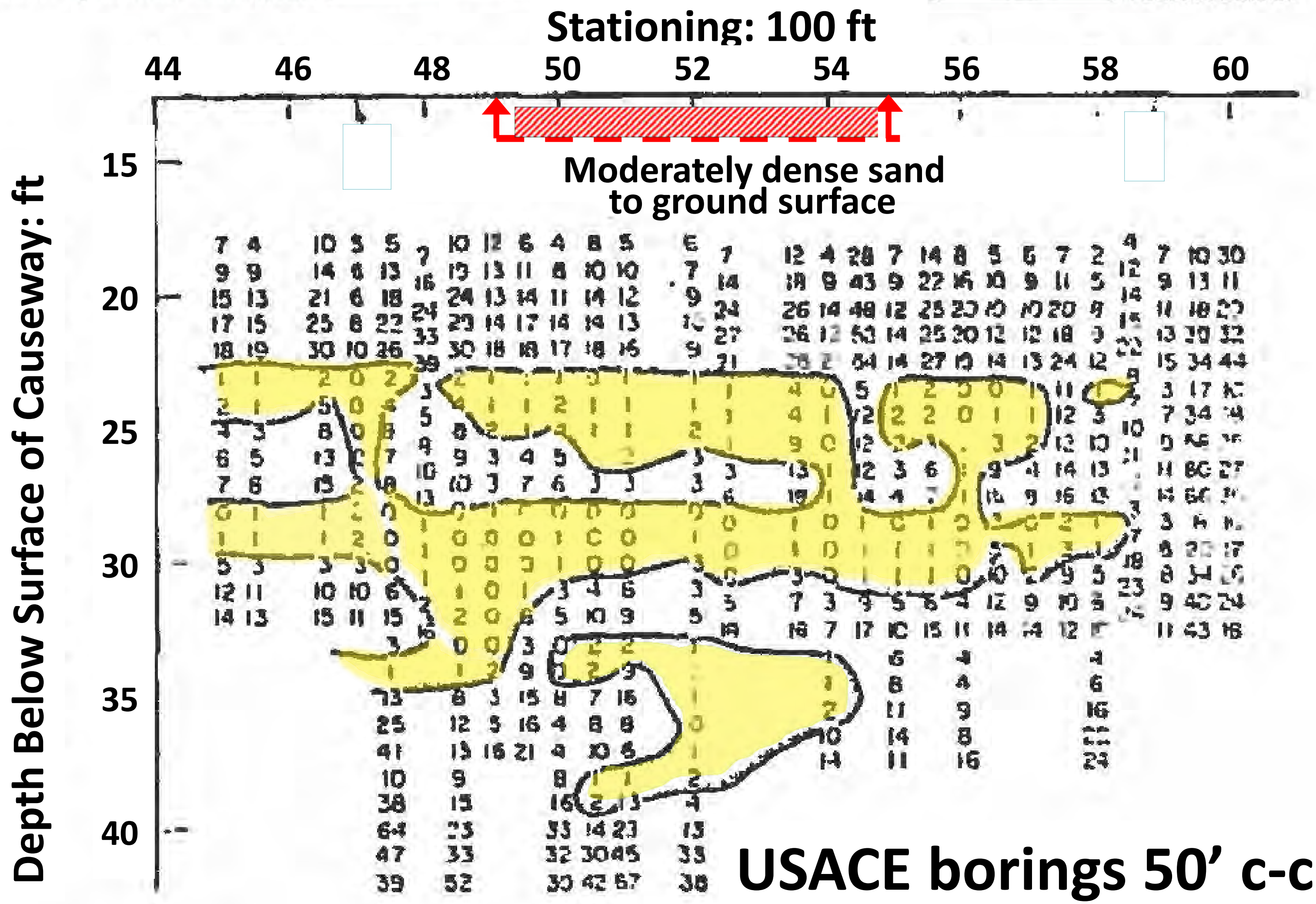


1967 Loose zones under Crawlerway B

Kennedy Space Center
Center Operations Directorate

Study Area - Loose zones under Crawlerway B (Peck 1969)

Facilities Division



2008 Field Testing Plan at R. Peck's worst Location (CWB)

Kennedy Space Center
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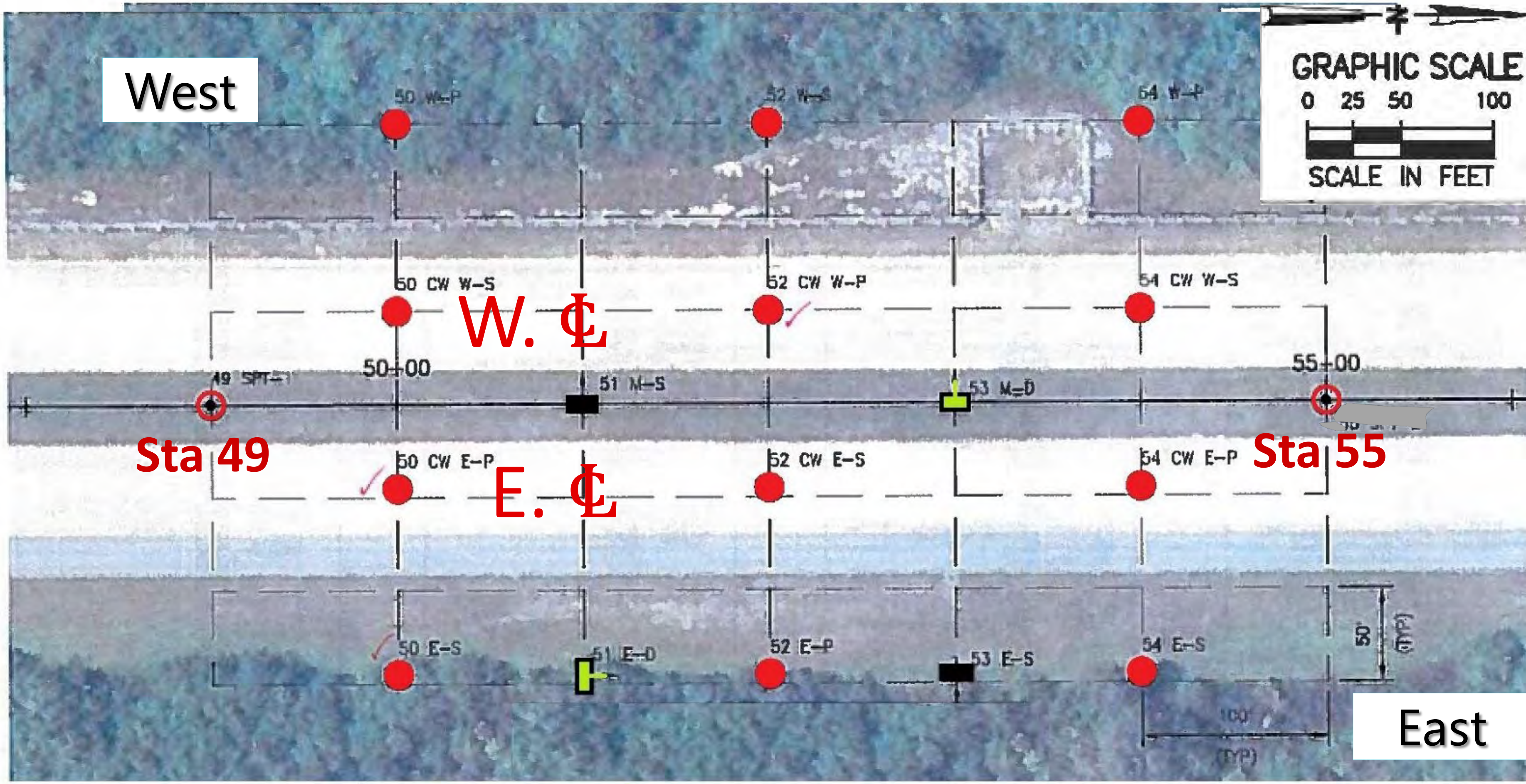
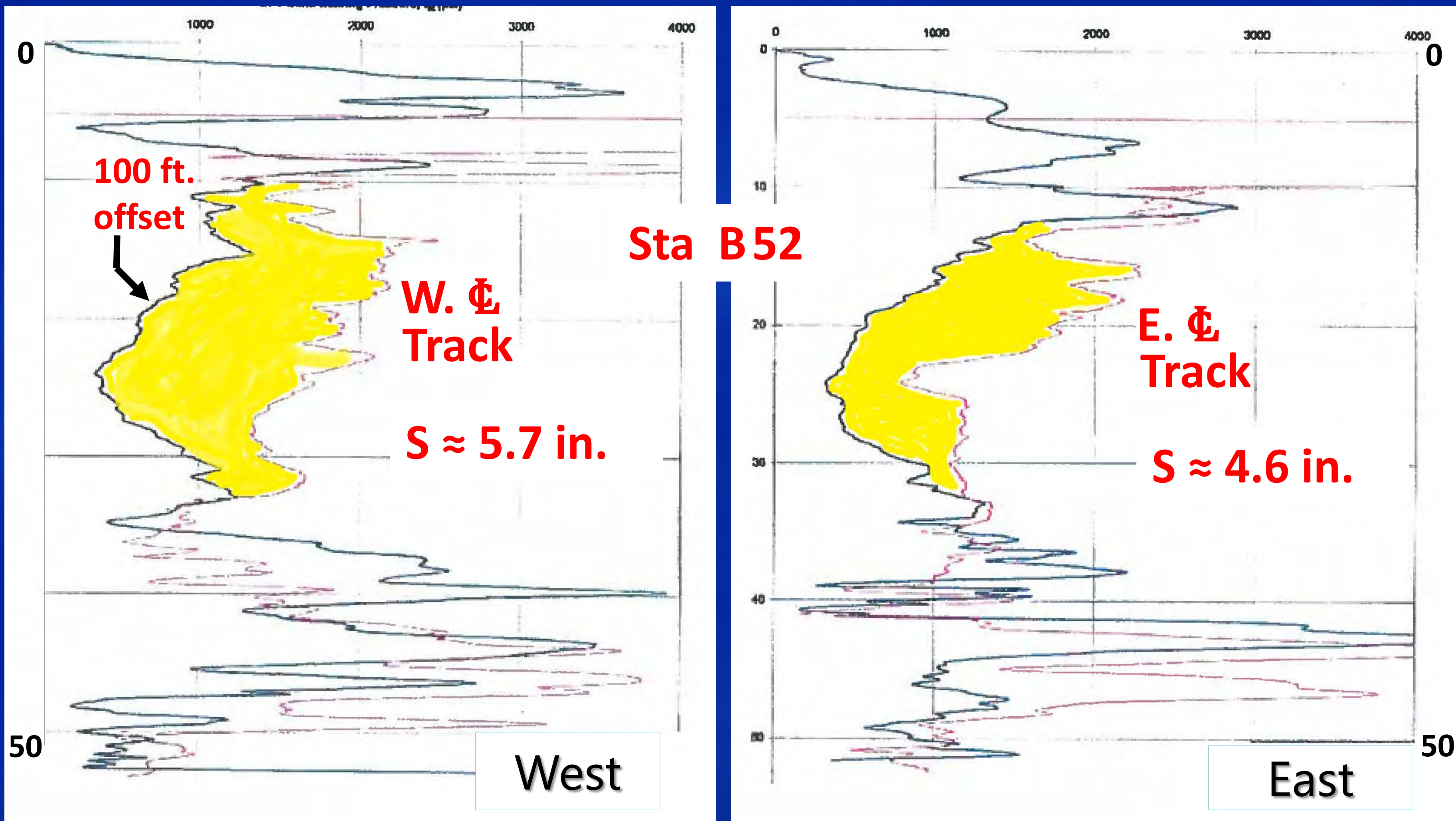


SDMT (with V_S)　DMT　(S)CPTU　SPT

Comparison of CW E & W ℄ and 100' offset CPT q_c profiles, with estimated 1967-2008 settlement, s, based on q_c - D_r changes from Italian chamber tests



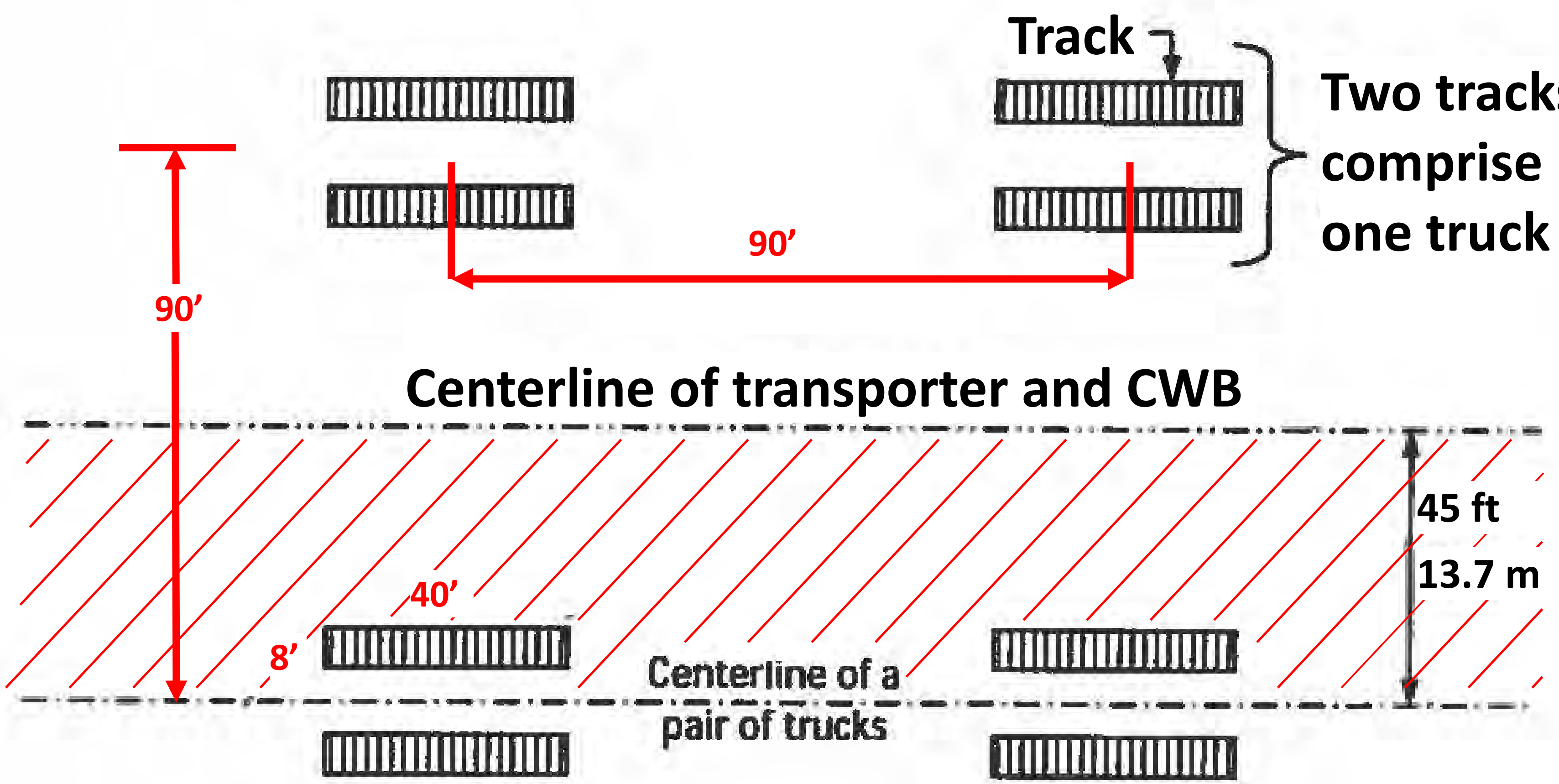
1 of 8 Tracks

Approx. Speed
0.2-1.0 mph

6” Vertical Adjustment

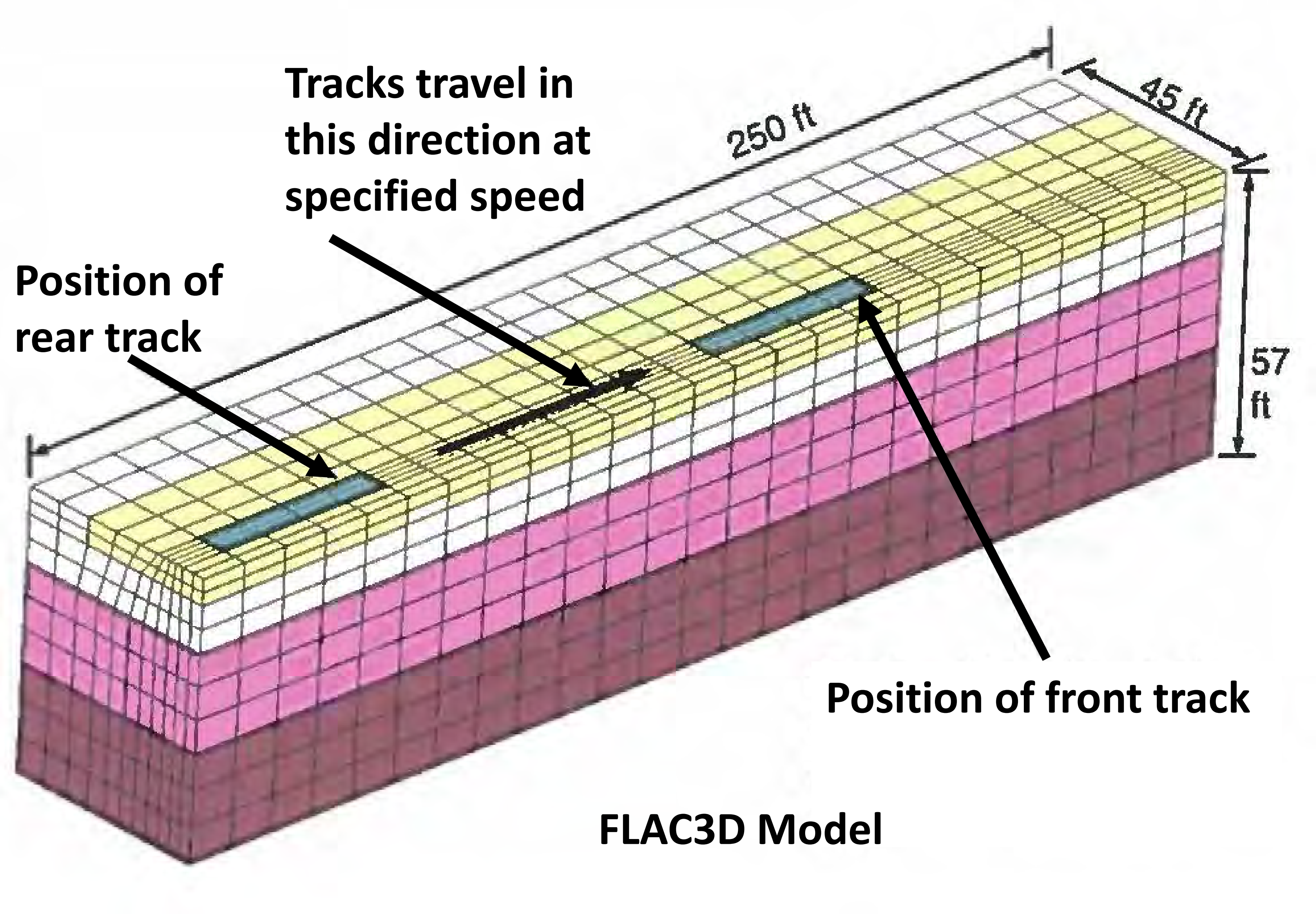
JHS   George Filz   Robert Edmunds

Use of Symmetry in Model

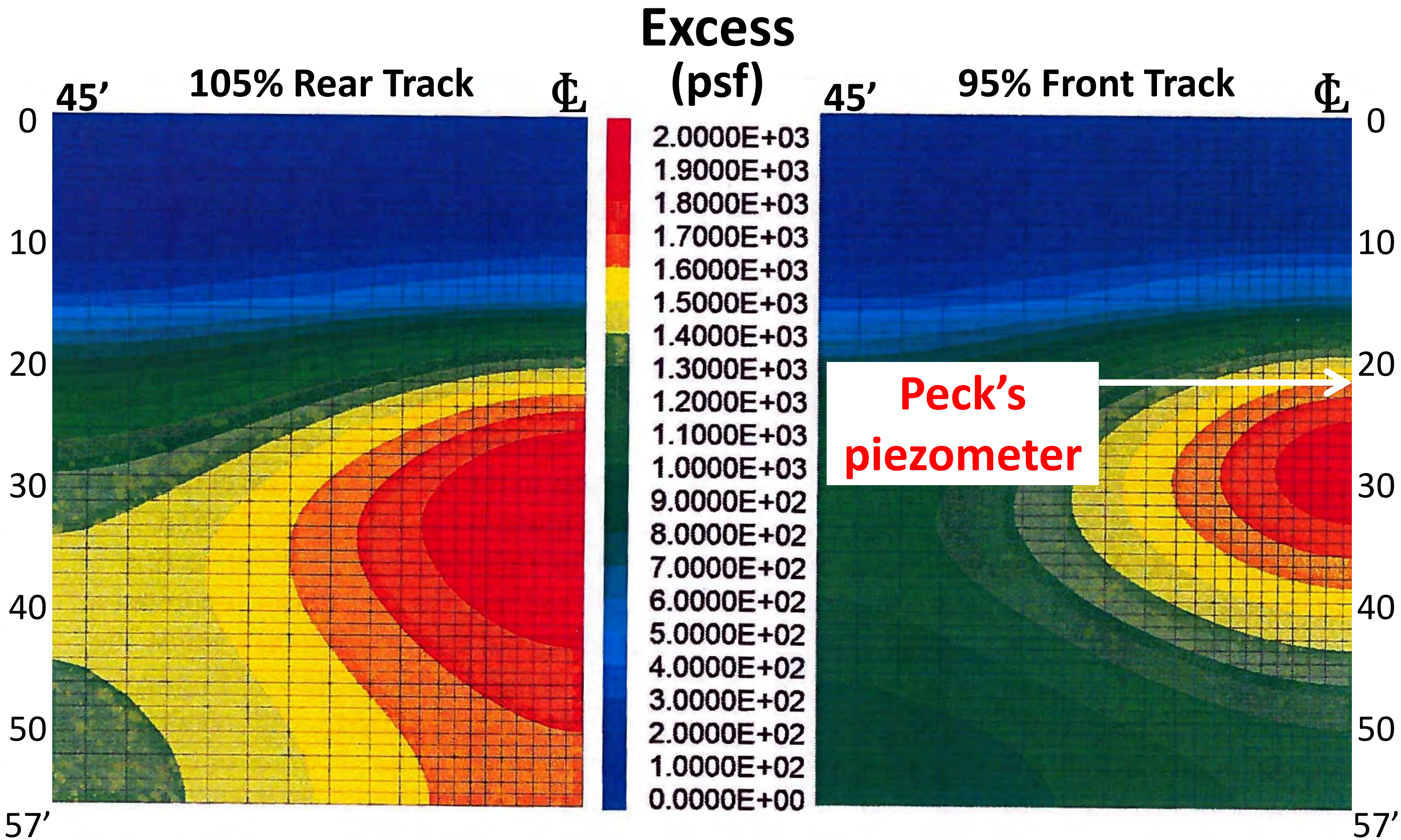


Plan View of Transporter Tracks

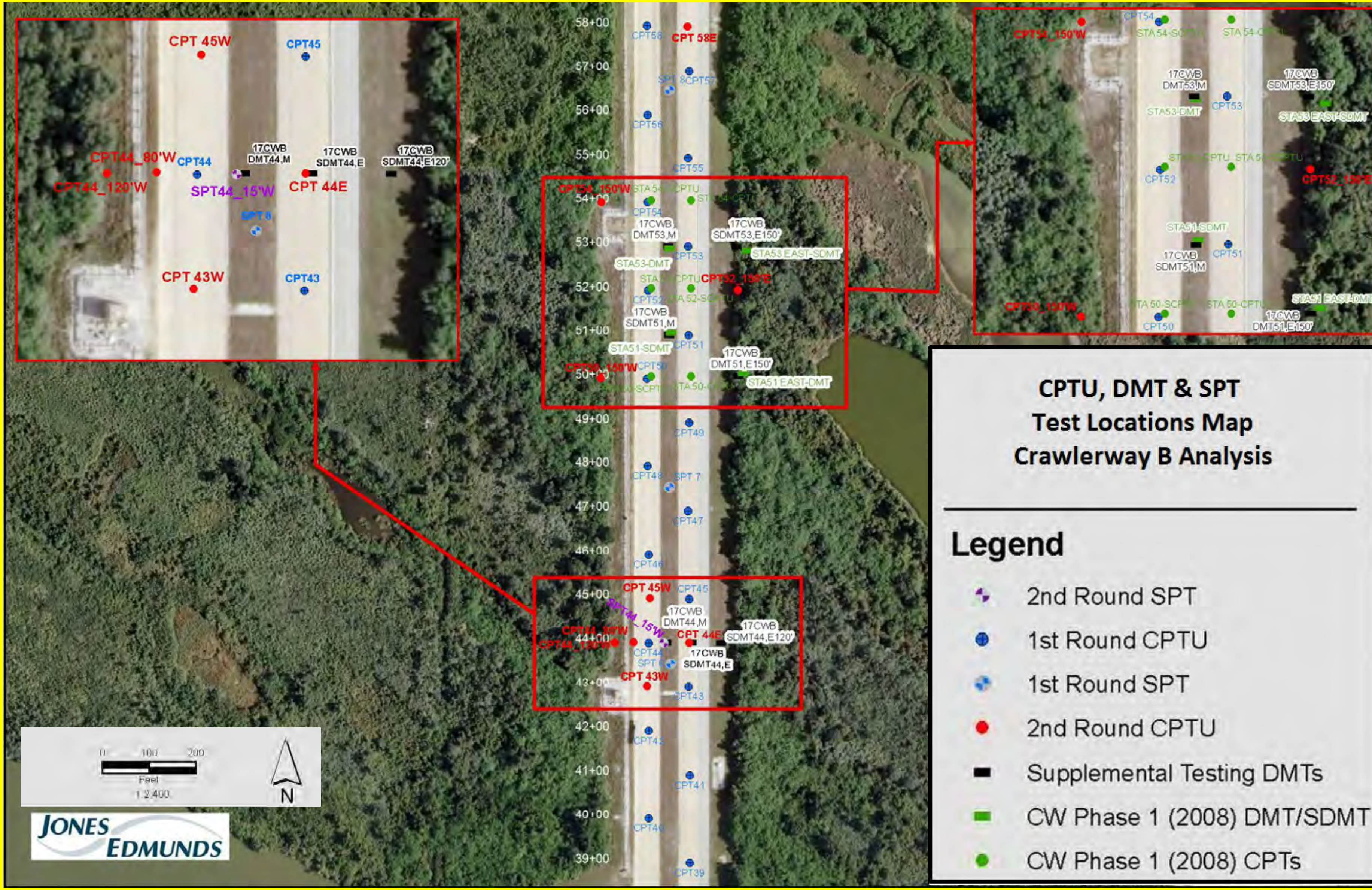
Model and Movement of Tracks



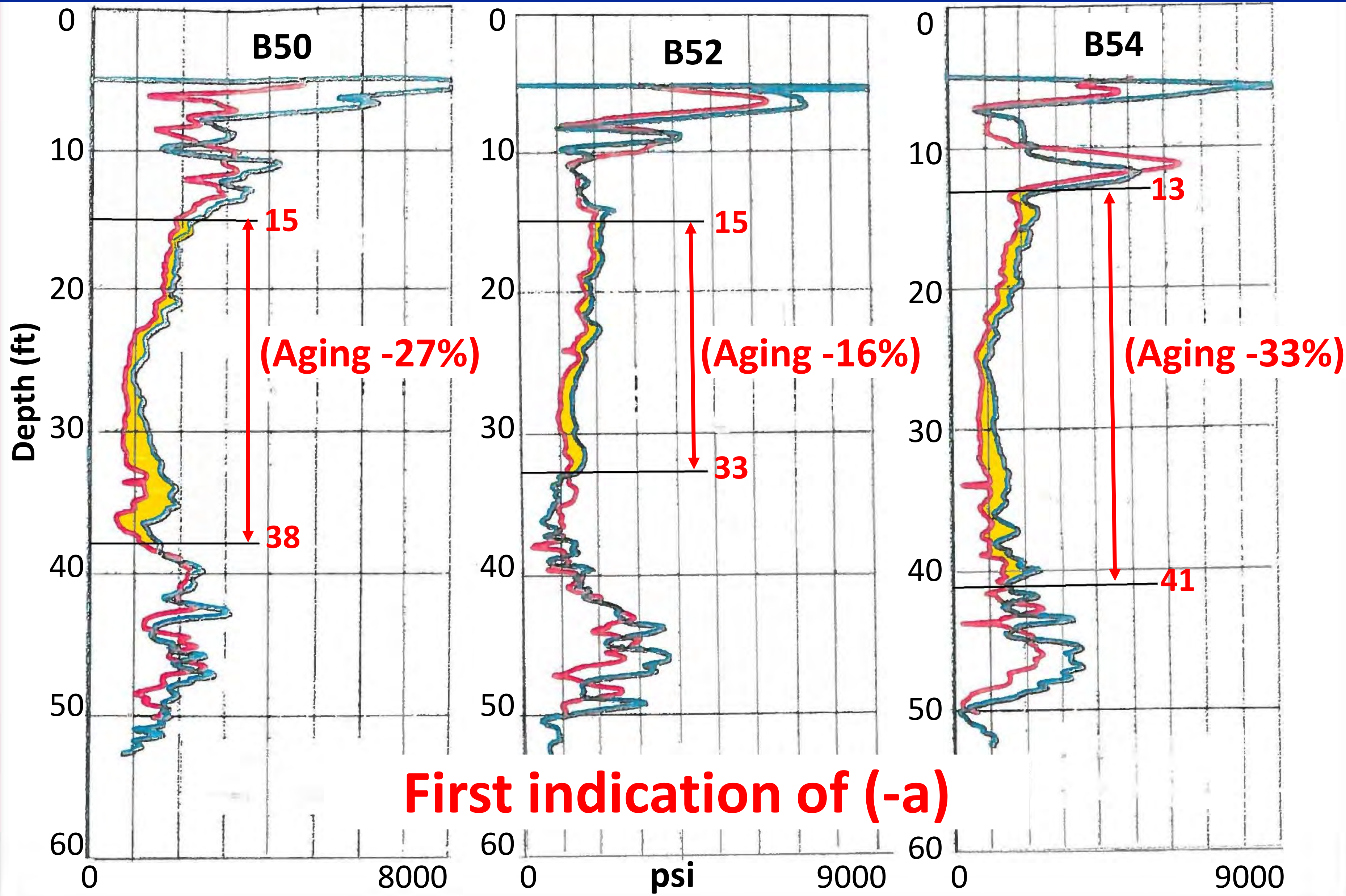
Cross-Sections showing Contours of Excess Pore Water Pressure (psf) from FLAC3D Match with Peck's 1967 Data



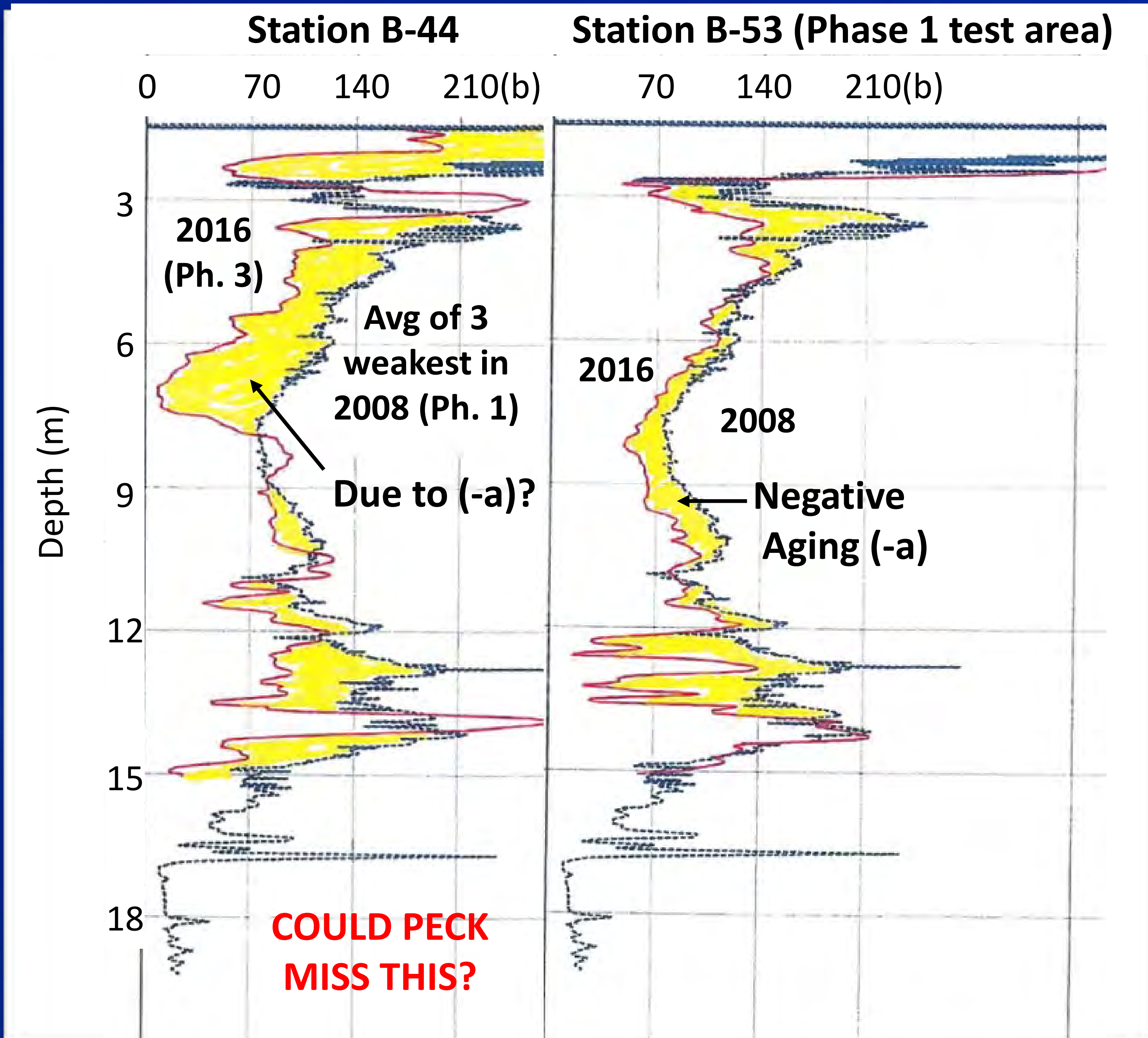
Air Photo Plan of 2016/17 Field Tests in CWB



CPT q_c Profiles, Under ℄ Tracks, 2008 (blue) 2016 (red)
No New Loadings – Direct Comparisons

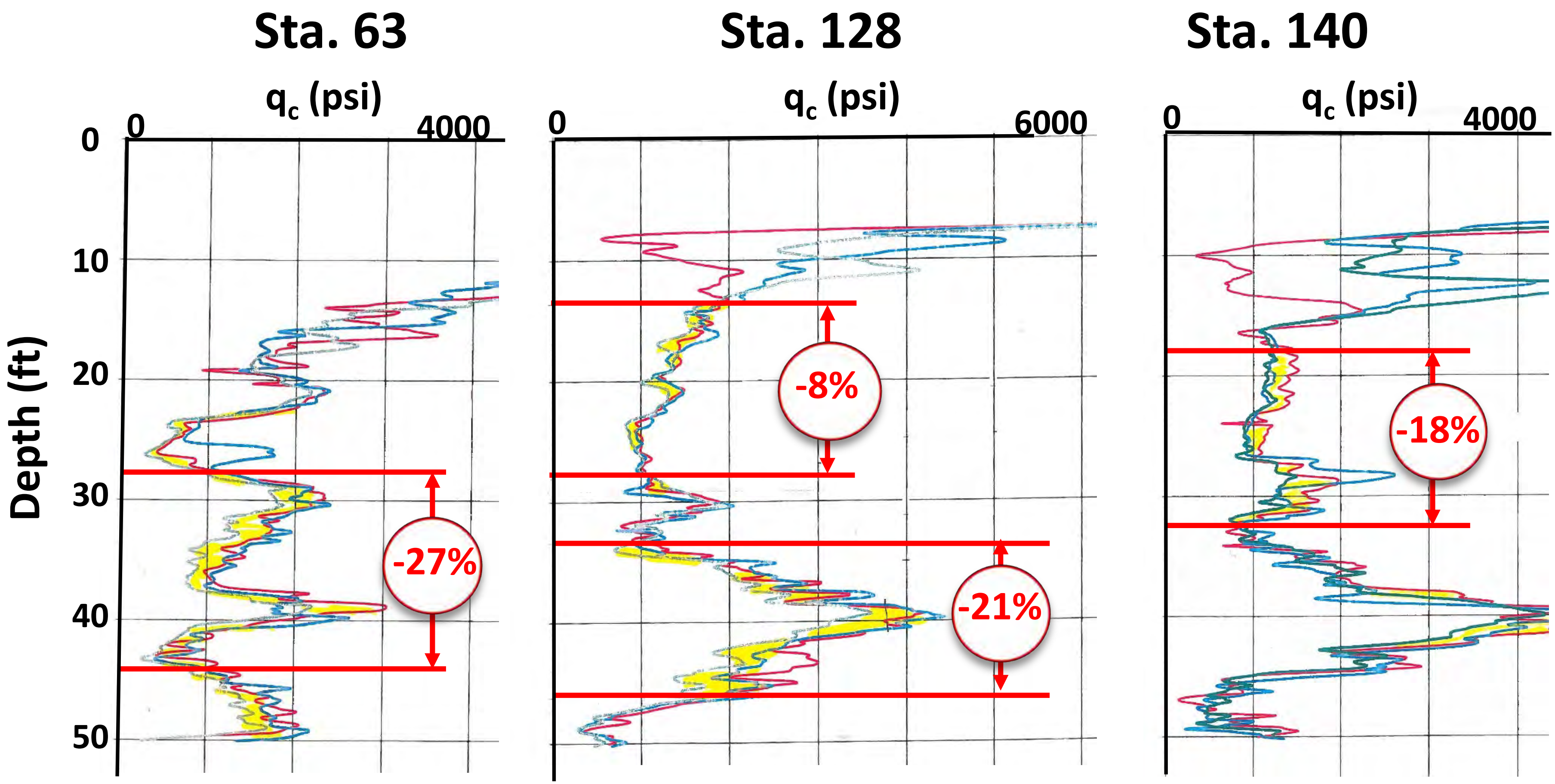


First indication of (-a)



Comparing CPT q_c profiles under CWB tracks, Peck's (1969 R.L.) weakest in 1967 vs. weakest found in 2016 (Ph. 3)

Last Heavy Rollout 2011, CPTs in 2009 and 2017
Examples of Negative Aging Under CWA



2009 CPT **2017 CPT**

N = 95 **N = 155** **N = 155**

Heavy Rollouts (Vs. N = 56 on CWB)

Hypotheses Considered for Cause of Negative Aging

hA - Creep reduction of residual lateral stresses produced in CW foundations under the moving CT, Chamber Research shows [$q_c \; \alpha \; \Delta\sigma'_h$]

Some Evidence

hB - Accelerated Solution of calcite (shell fragments) by acid rain flowing downward into lagoon sands, which increases void ratio and weakens the sands.

Much

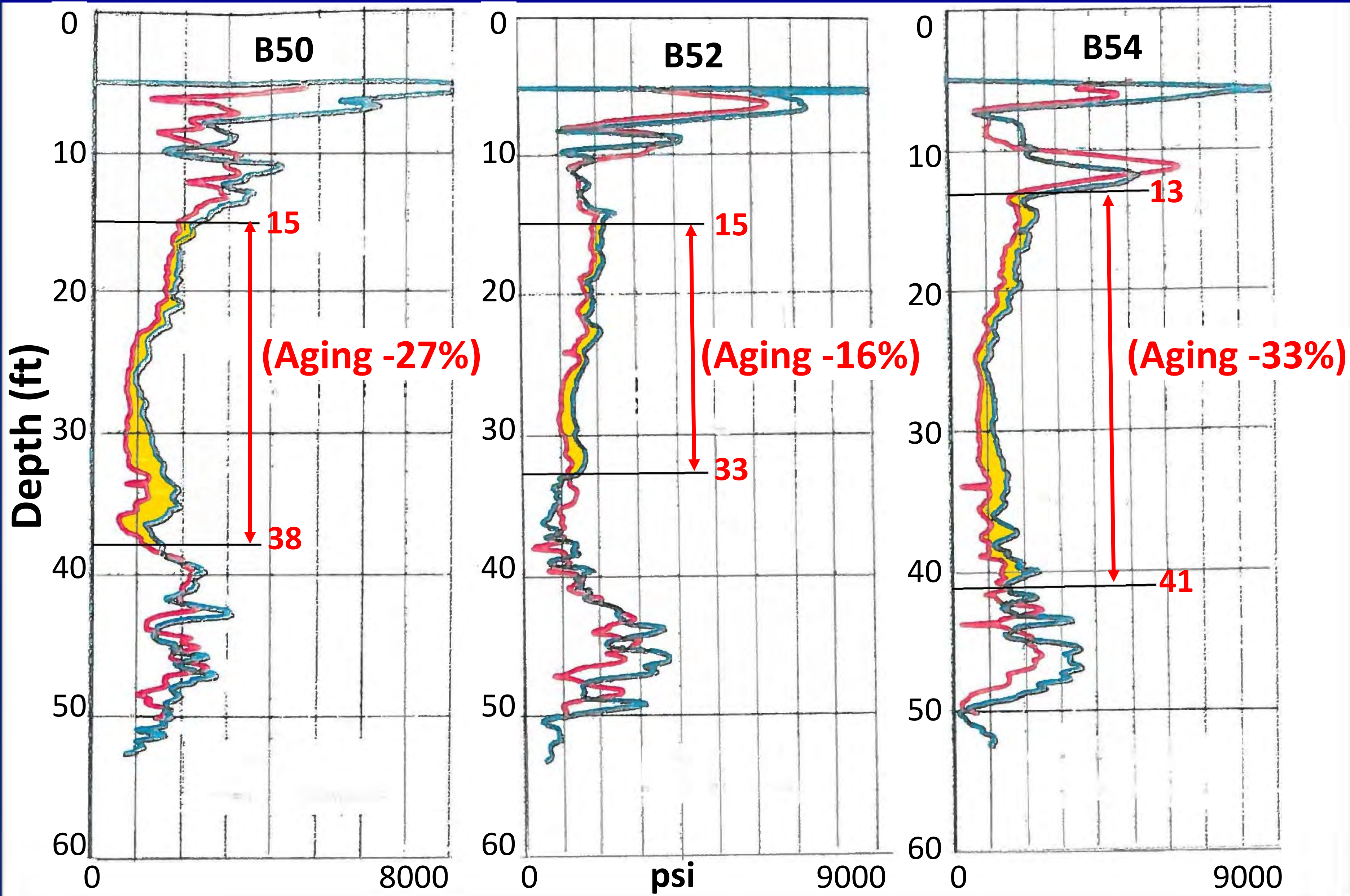
hC - Downward erosion of – 200 fines into underlying shelly layers, which similarly weakens the sands.

None

hD - Decay of overhead organics, which also weakens surrounding sands and produces organic acids that accelerate the hB solution of calcite.

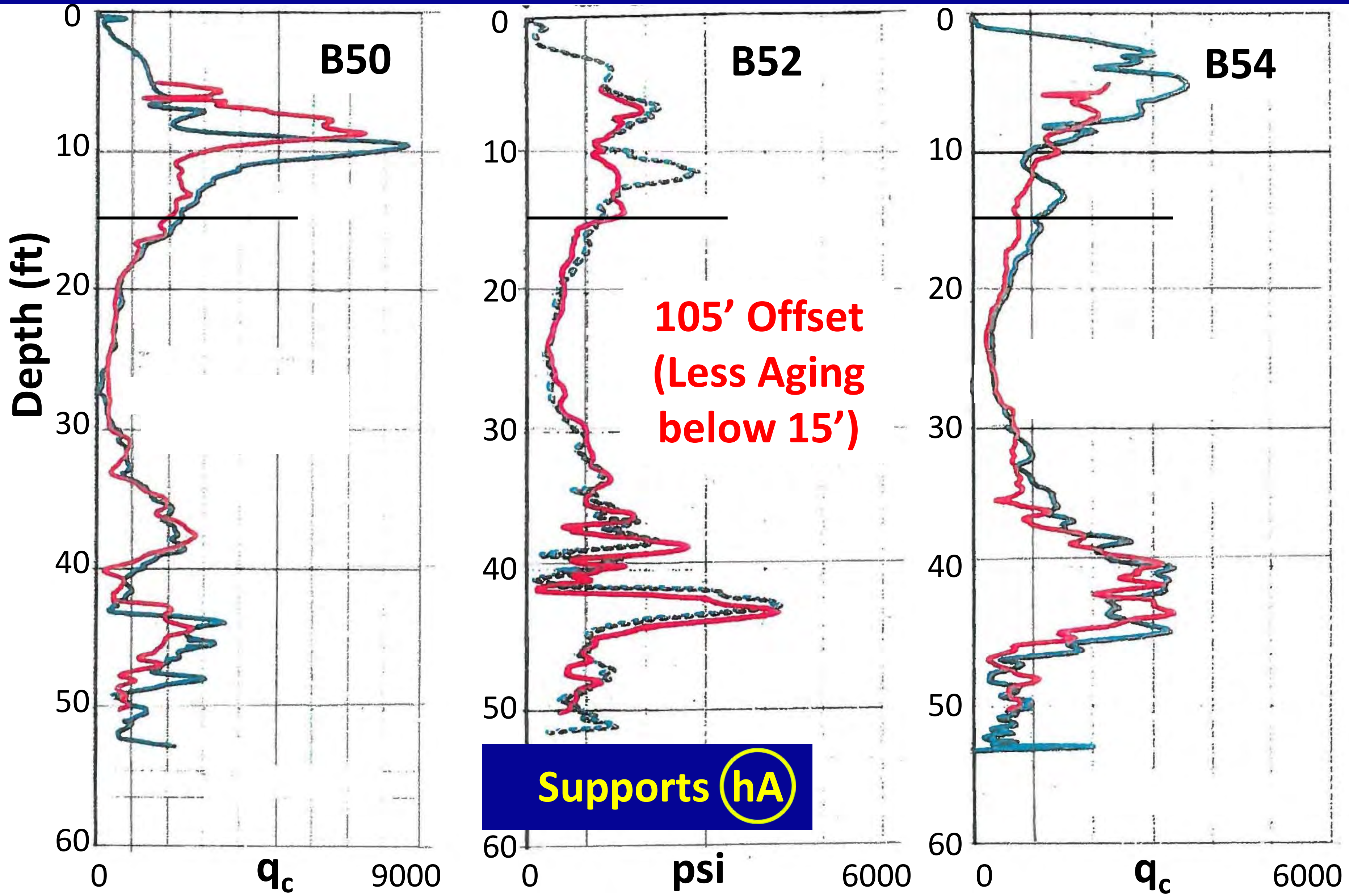
Some

CPT q_c Profiles, Under ℄ Tracks, 2008 (blue) 2016 (red)
No New Loadings – Direct Comparisons



CPT q_c Profiles, 105' Offset from ℄ Tracks, 2008 (blue) 2016 (red)

No New Loadings – Direct Comparisons



Discussion of "Experimental and DEM Examinations of K_0 in Sand under Different Loading Conditions" by Y. Gao and Y. H. Wang

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G. Mesri, M.ASCE[1]; and Cai Wang[2] 2015

[1]Ralph B. Peck Professor of Civil Engineering, Univ. of Illinois at Urbana-Champaign, IL 61801, Hong Kong, China (corresponding author). E-mail: gmesri@illinois.edu

[2]Graduate Student, Univ. of Illinois at Urbana-Champaign, IL 61801, Hong Kong, China.

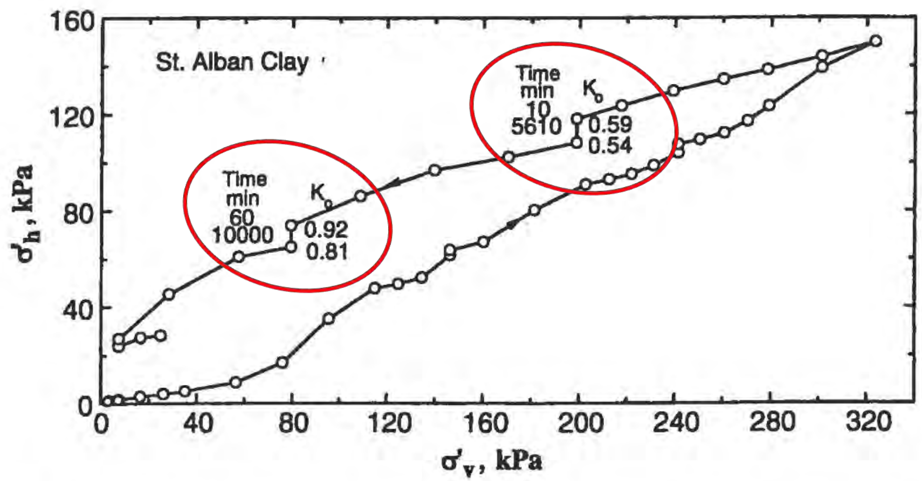


Fig. 1. Decrease in K_o during secondary rebound in an odometer; 10 and 60 min are the duration of end of primary rebound, 5,610, and 10,000 min are the elapsed time including secondary rebound (data from Mesri and Hayat 1993)

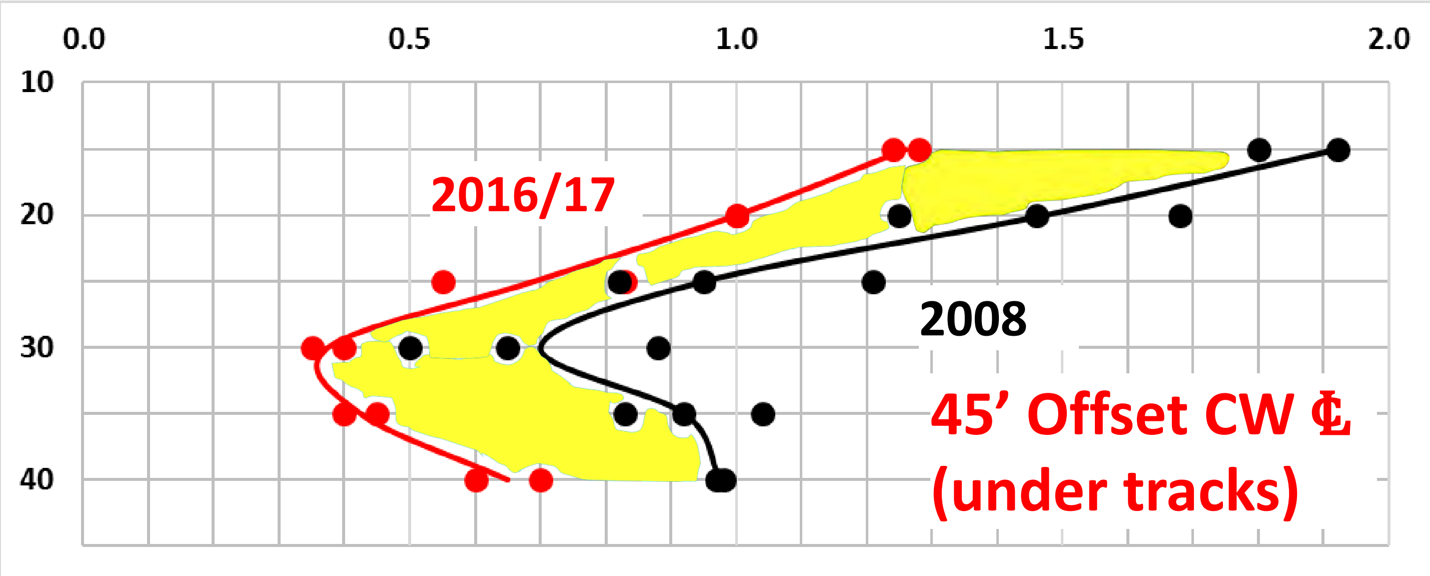
Mesri and Wang provide a Method for Estimating the Future Secondary Lateral Stress Creep Rate in Sands and Silts

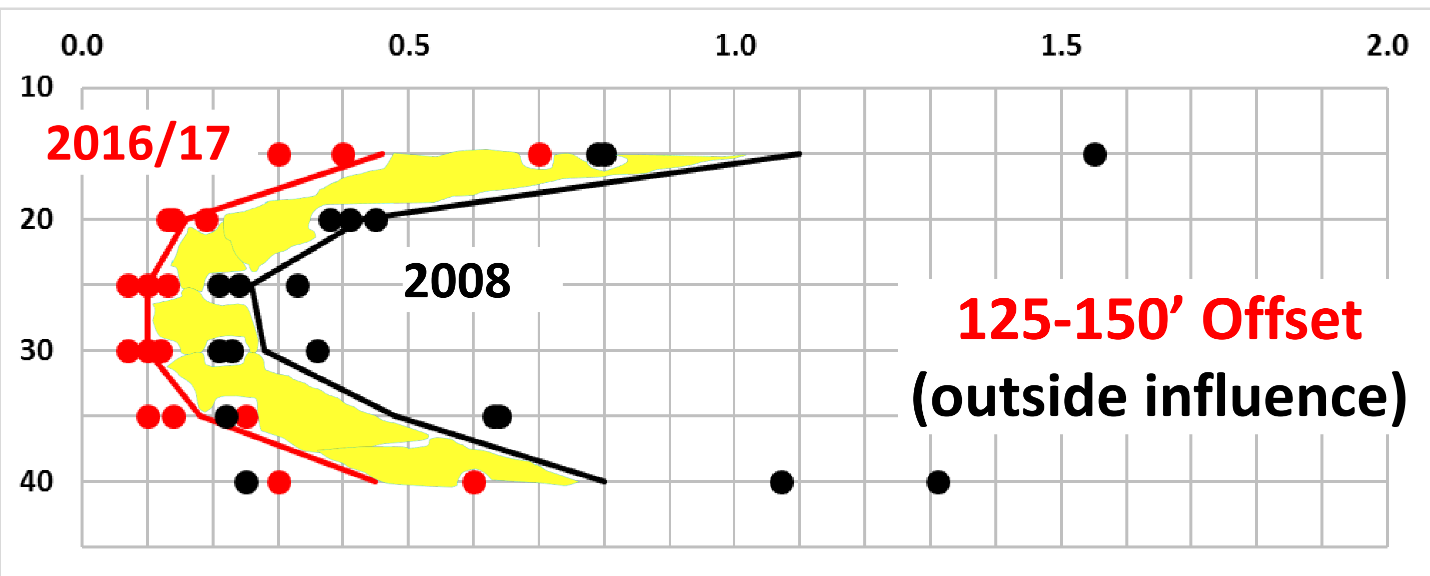
$$K_o = \frac{[K_o]_{t_p}}{\left(\frac{t}{t_p}\right)^{C_{s\alpha}/C_s}} \qquad (2)$$

$$\frac{C_{s\alpha}}{C_s} = \alpha(\mathrm{OCR})^{1/2} \qquad (3)$$

Supports hA

f_s = CPT unit side shear (tsf)

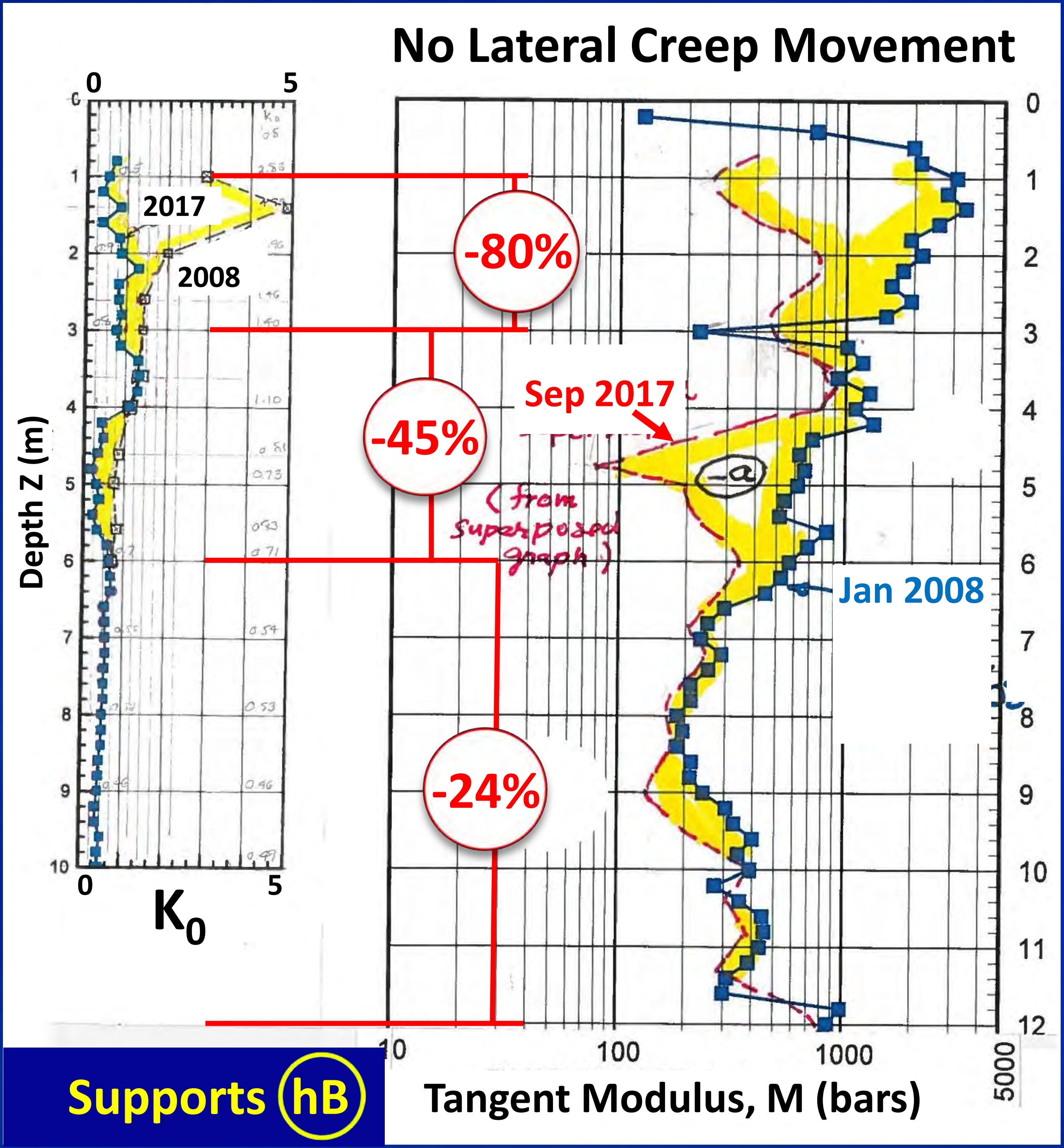




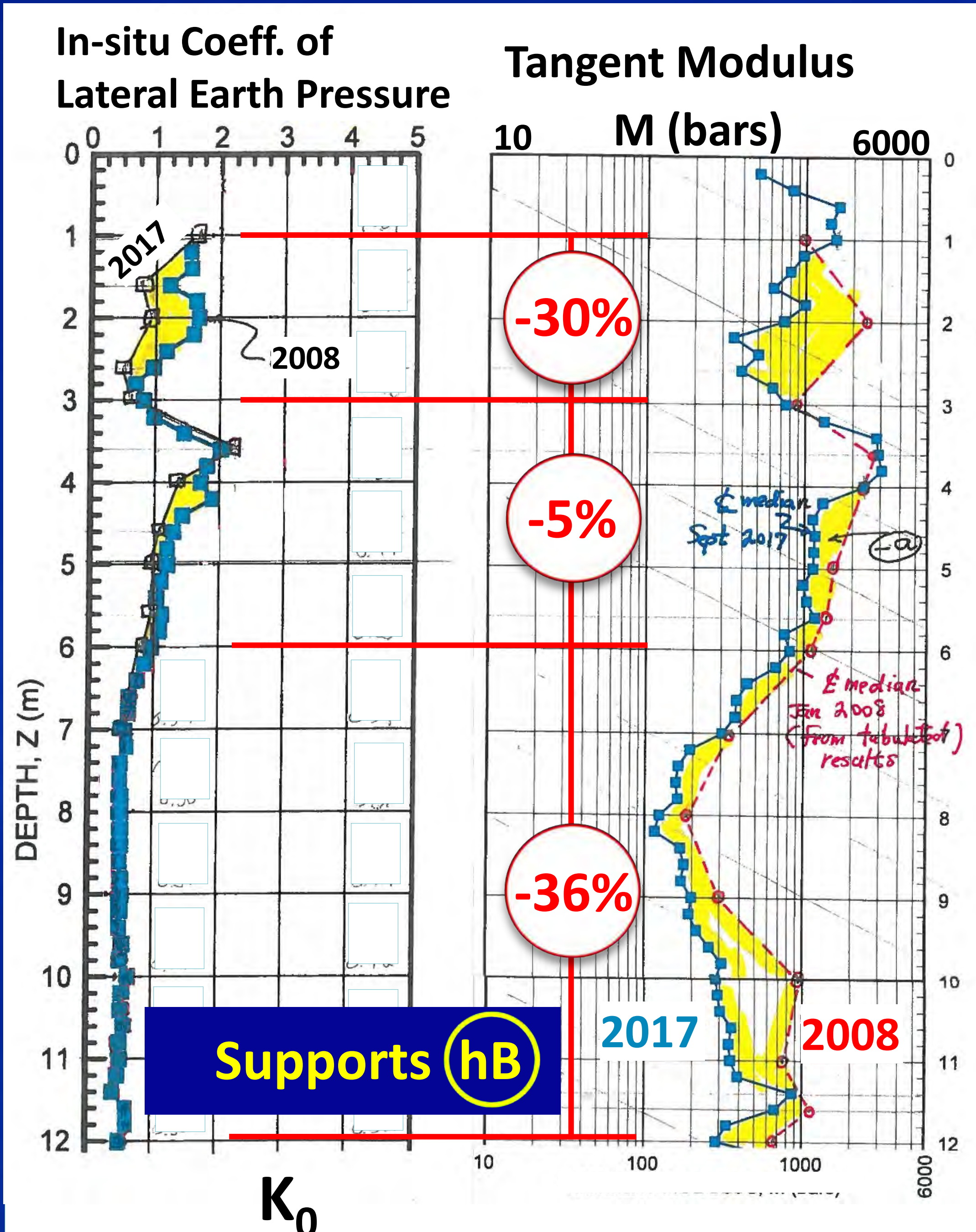
Direct Comparisons between 2008 and 2016/17 CPT unit side shear in B50-B54 Test Area

Similar pattern in both offsets suggests same cause

Supports hB



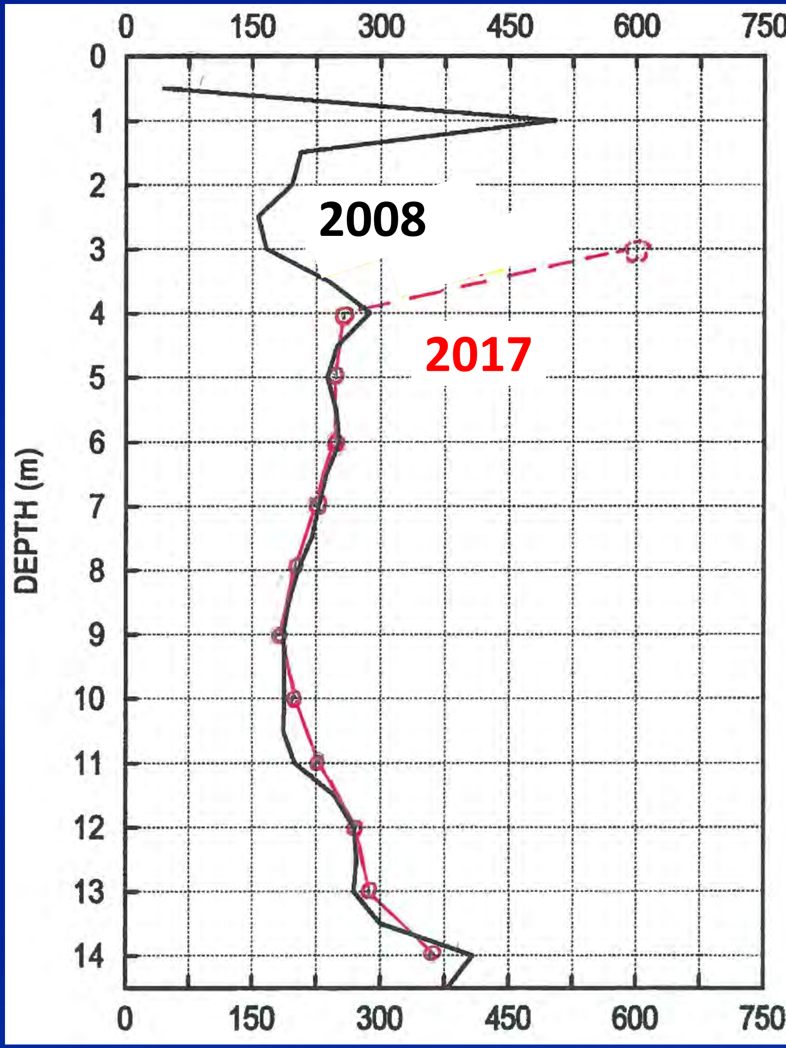
Negative Aging, 2008 – 2017, DMT ℄ Median Direct Comparisons of Predicted K_0 and M at Test Area Sta. B 51



Negative Aging, 2008 – 2017, DMT ℄ Median Direct Comparisons of Predicted K_0 and M at Test Area Sta. B 53

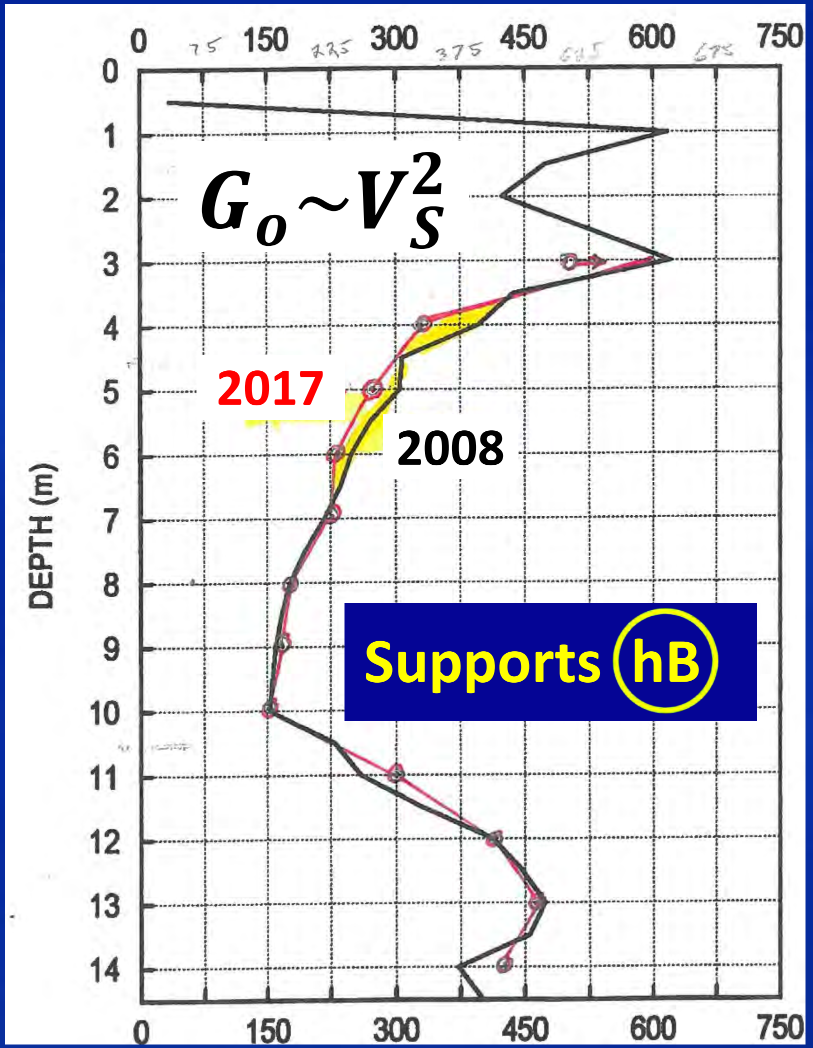
CWB Test Area 2008/2017 V_s Direct Comparisons

Shear Wave Velocity V_s (m/s)



V_s less sensitive to negative aging

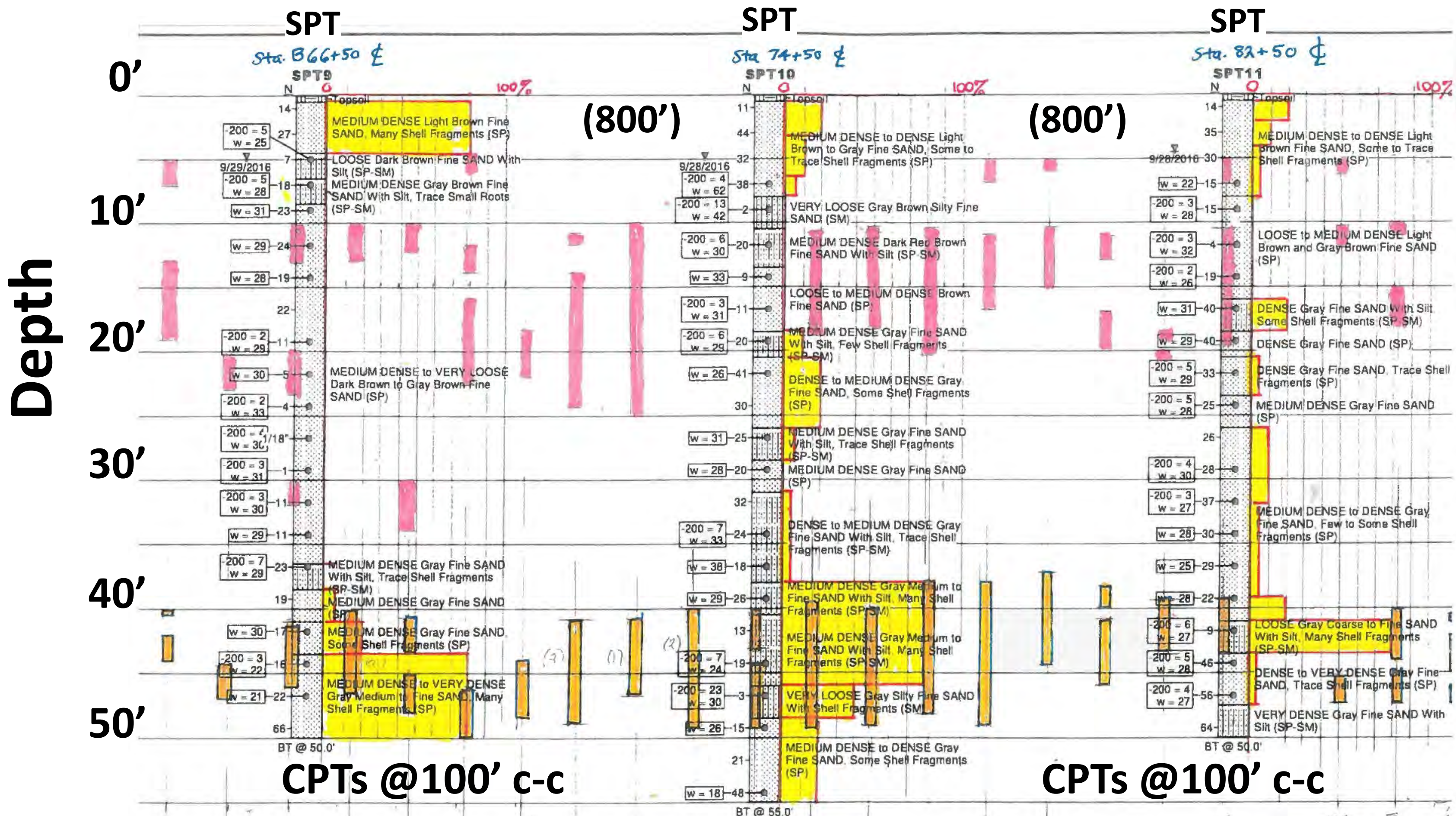
Shear Wave Velocity V_s (m/s)



B51 Median ℄

B53 Offset c. 135'

CWB Section with Expected Less Than Average Aging (-a)

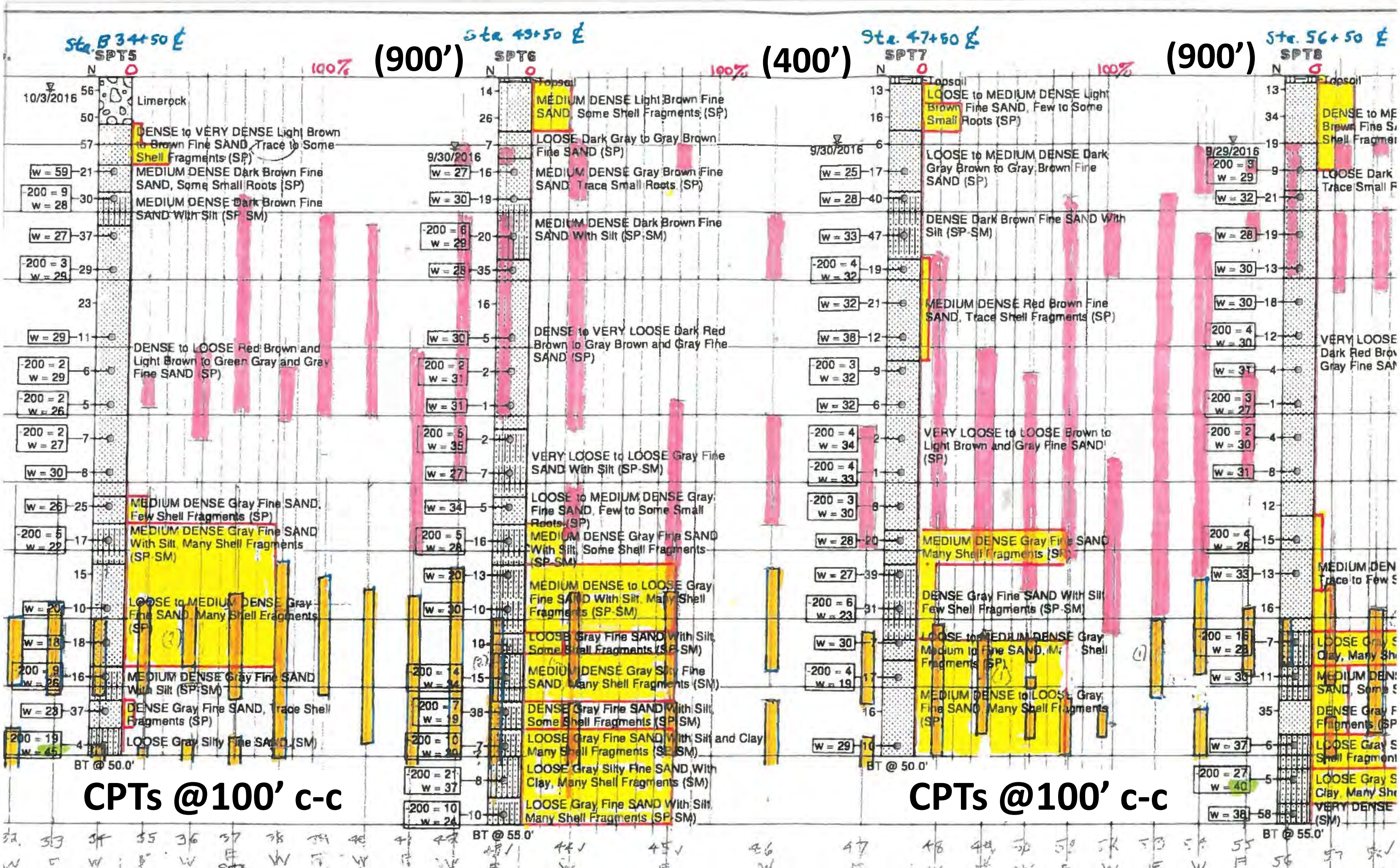


CPT q_c profile less than average 3 lowest in 2008 test section

Estimated % shell

SPTs @ CWB median CPTs @ 45 offset under tracks

CWB Section with Expected More Than Average Aging (-a)

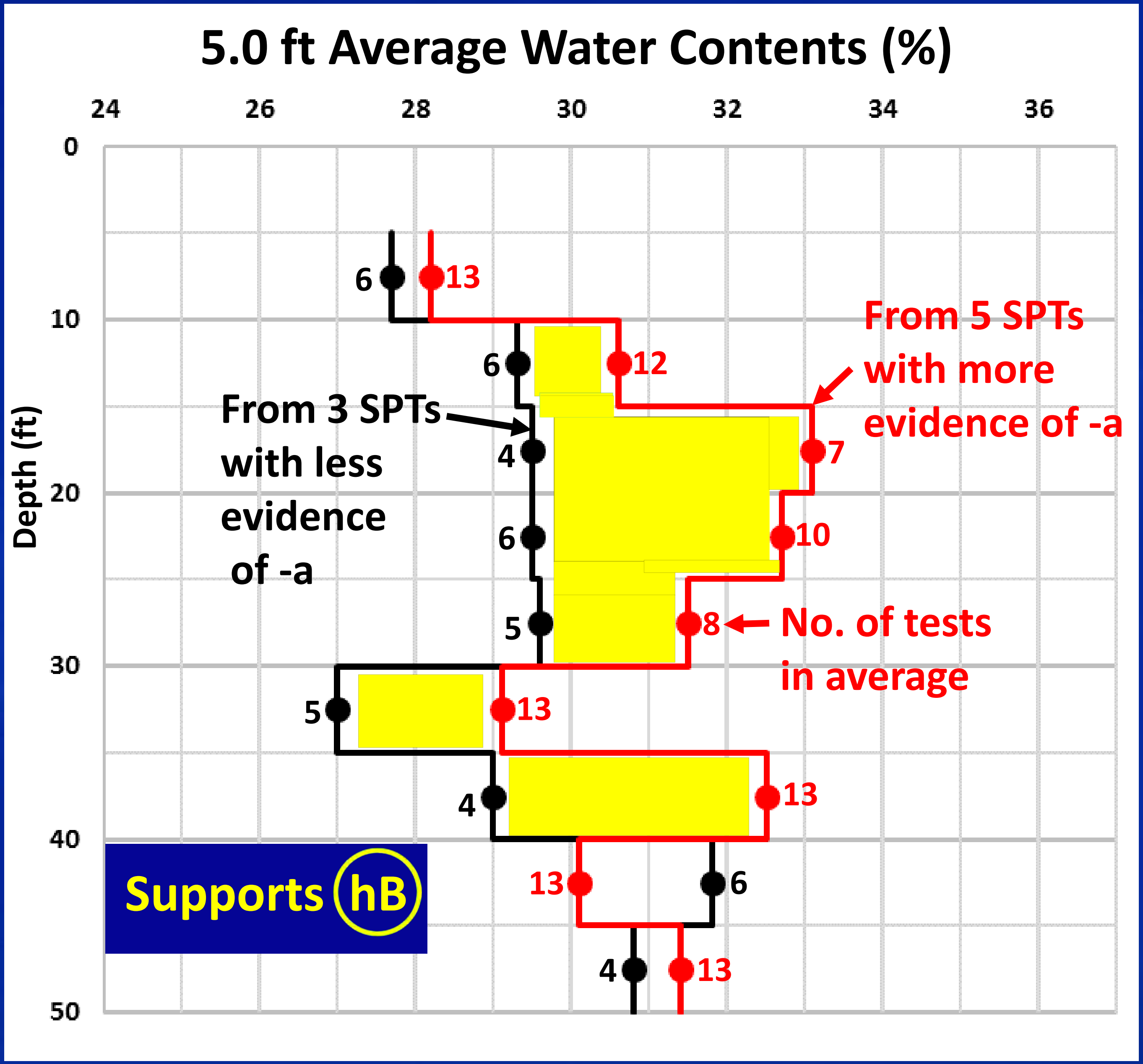


CPT q_c profiles less than average 3 lowest in 2008 test section

Estimated % shell

SPTs @ CWB median
CPTs @ 45' offset, under tracks

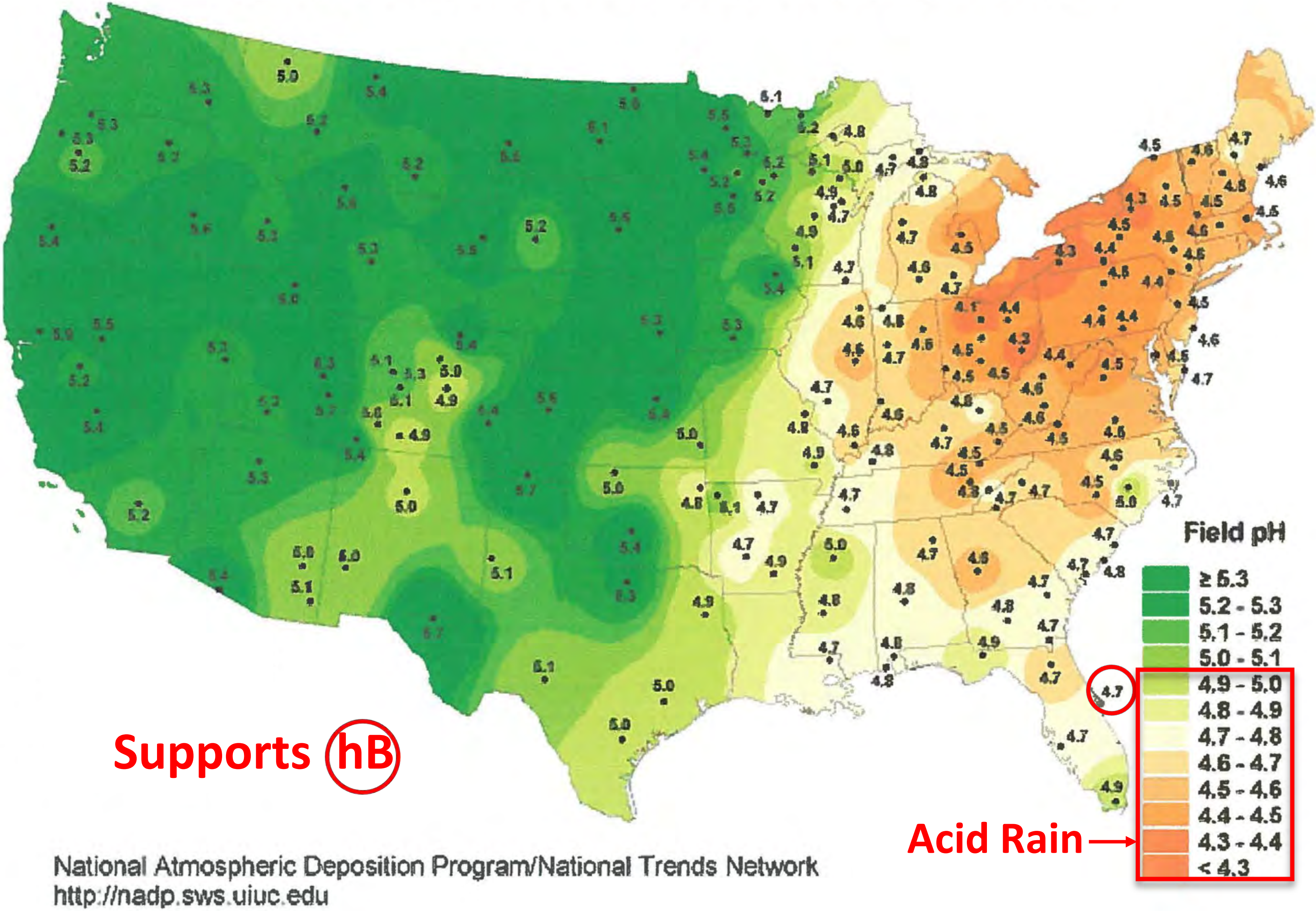
Average +Δw = 2.6%, suggests Calcite (shell) solution



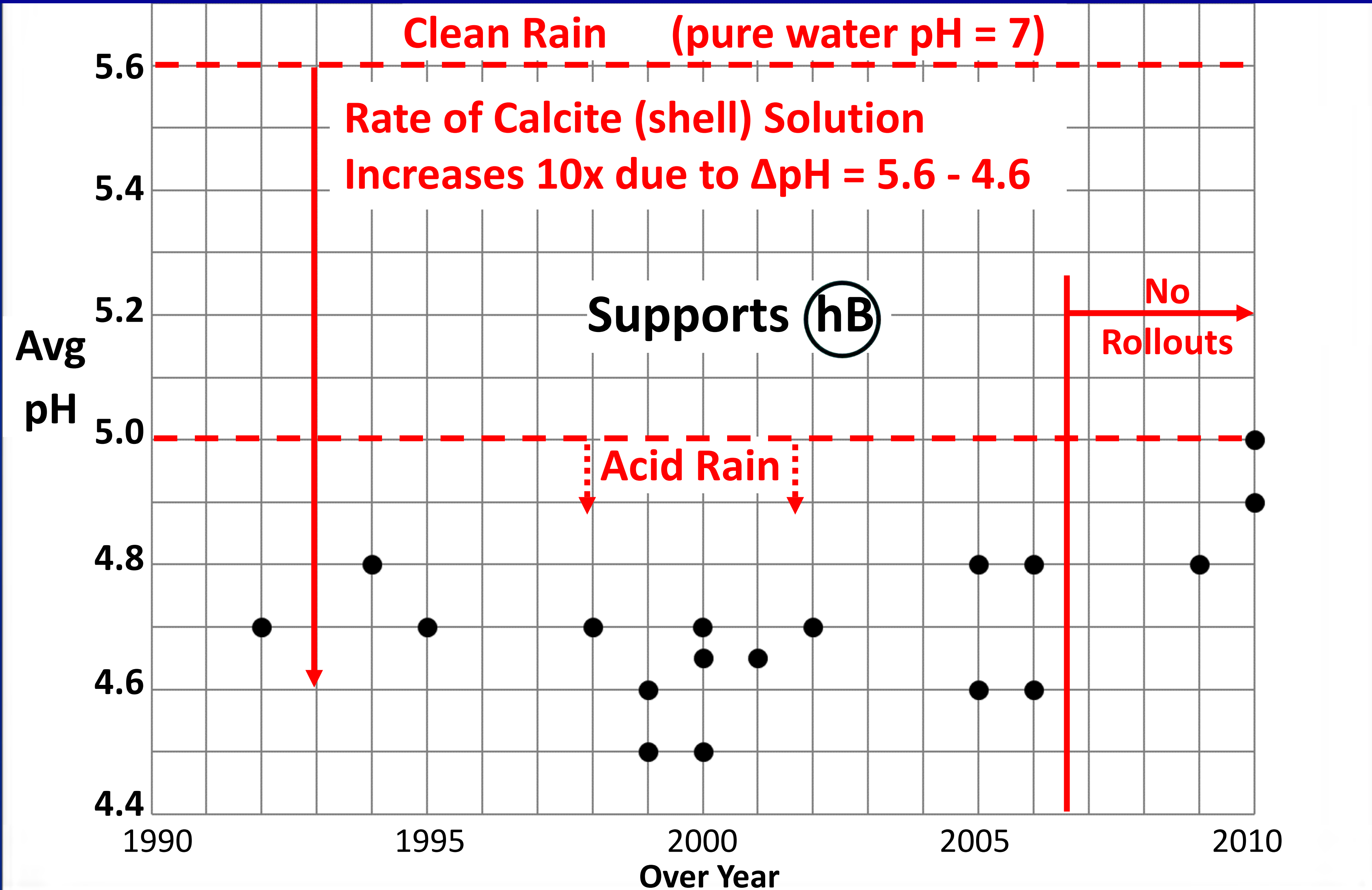
Comparison of Average water content between parts of CWB with more and less than average evidence of negative aging

Note: Another comparison, with 4 SPTs each, gave Δw over 10-40' = +1.0%

Hydrogen ion concentration as pH of precipitation, 2002



History of Yearly Rainfall Average pH Values at Kennedy Space Center (from Google)



Rocket Exhaust Clouds Contribute to temporary reductions of pH in Acid Rain in Kennedy Space Center Area

Supports hB

- Studied extensively by NASA in 1980s, especially solid boosters
- ~ 70 tons per launch of HCl released below c. 3km
- Area affected 28km^2 with pH = 1-3
- Sometimes a 0.5 drop in pH 100km downwind
- Solids deposited on pad were wash-cleaned. Wash stored in ponds with pH ~ 1 to 2.

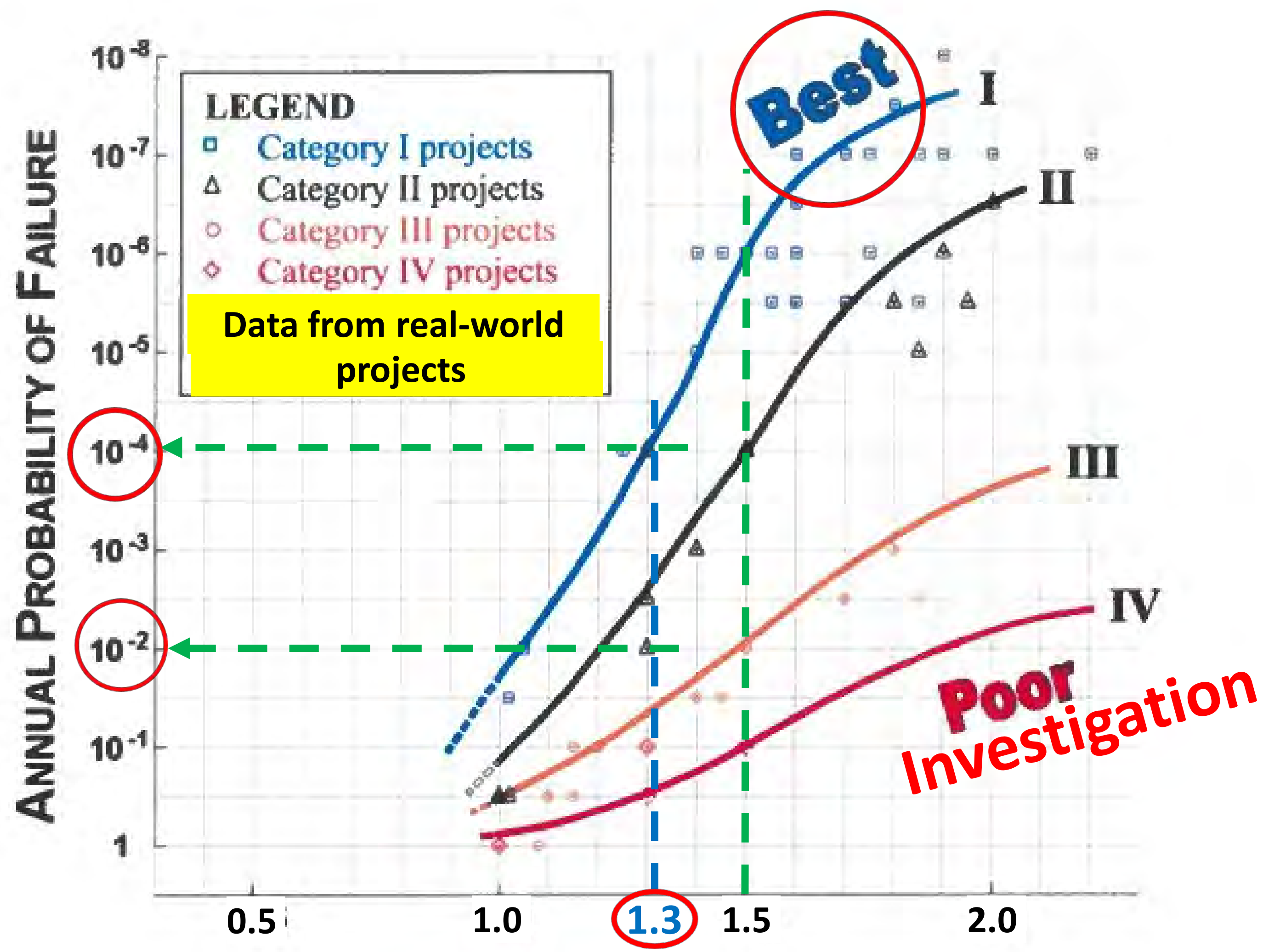
Comments

1. Exceptionally 'clean' 50-year case history of 6-9 years with negative aging in sands
2. Most likely due to effects of acid rain
3. Needs more investigation

Next Phase 4 (2020+)

4. Full scale CWAB conditioning
5. Improve prediction model
6. Plan future monitoring
7. Observational method
8. NASA wanted 99.99% reliability, now accepts 99%

Estimating Reliability from FS for Bearing Capacity and Slope Stability (Silva, Lambe, Marr 2008)



Factor of Safety (BC and SS) from FLAC3D

The End