



# Quantifying the Impact of Jointed Concrete Pavement Curling and Warping on Pavement Unevenness

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## **US FHWA Curl/Warp Study**

- o Impact of Curling and Warping on JCP Performance**

## Outlines

- **Curl/Warp Measurement**
- **Profile Synchronization and Joint ID**
- **2GCI Curvature Index**
- **RoCK System for Curvature-Impact-Roughness Analysis**

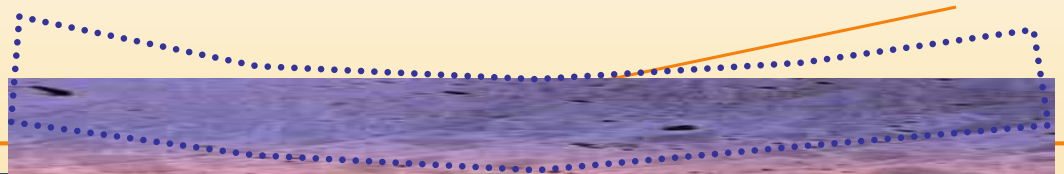
## Curl/Warp Measurement

### ○ What to be measured?

- Site Selection
- Data Collection

### ○ How to measure?

- Profiling
- Temperature
- Others

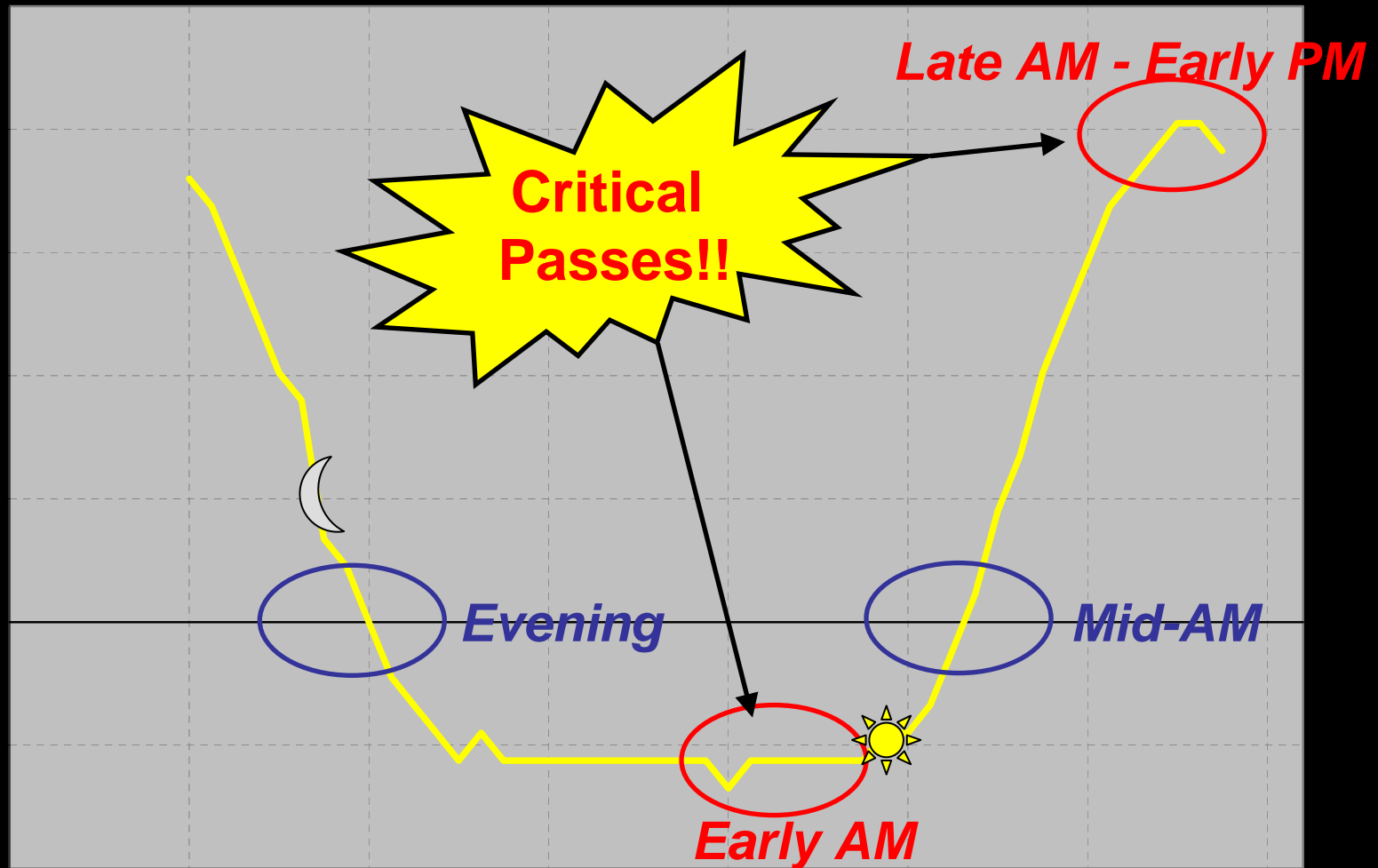


# Selected Sites

2008



# Diurnal Profiling



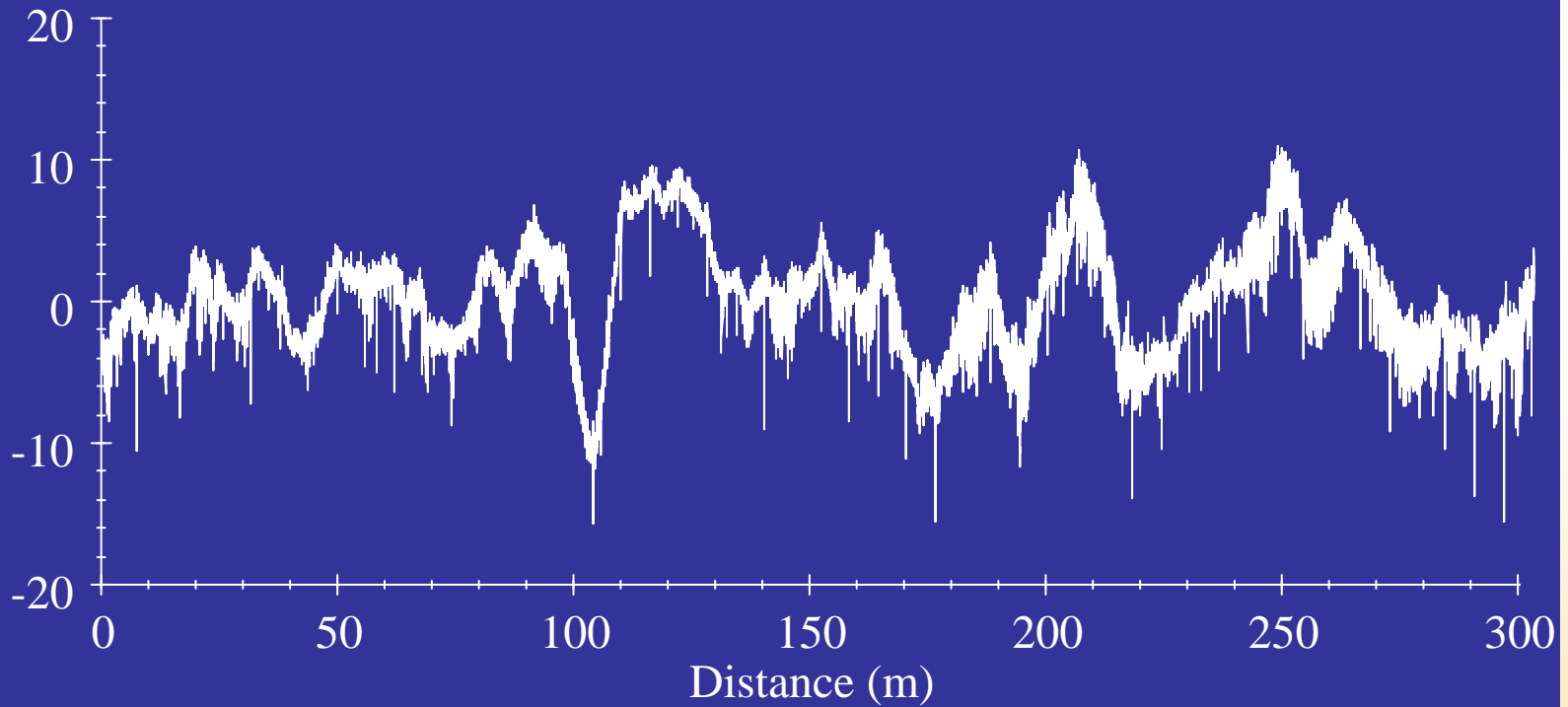
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# Raw Profile

IA\_023A

Left Elevation (mm)

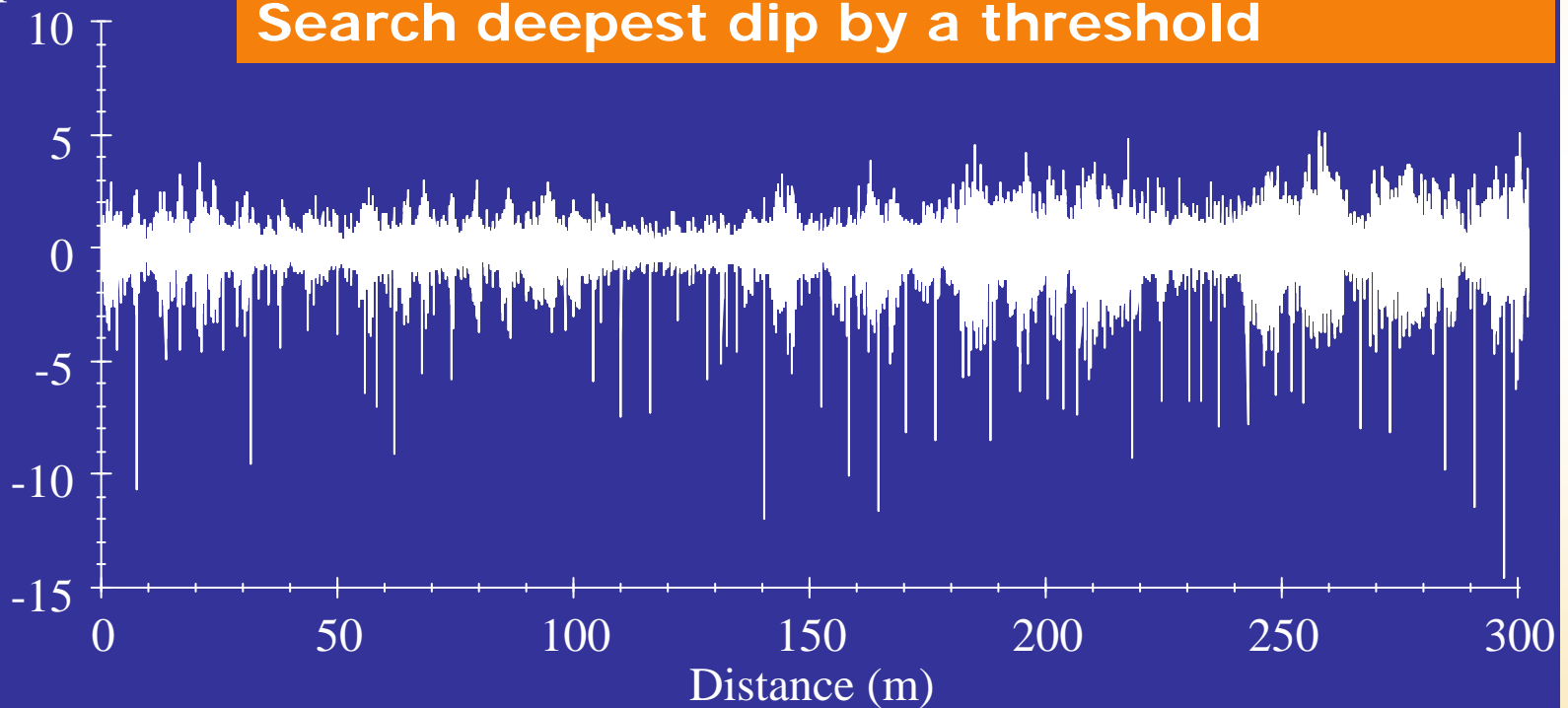




# Spike Profile

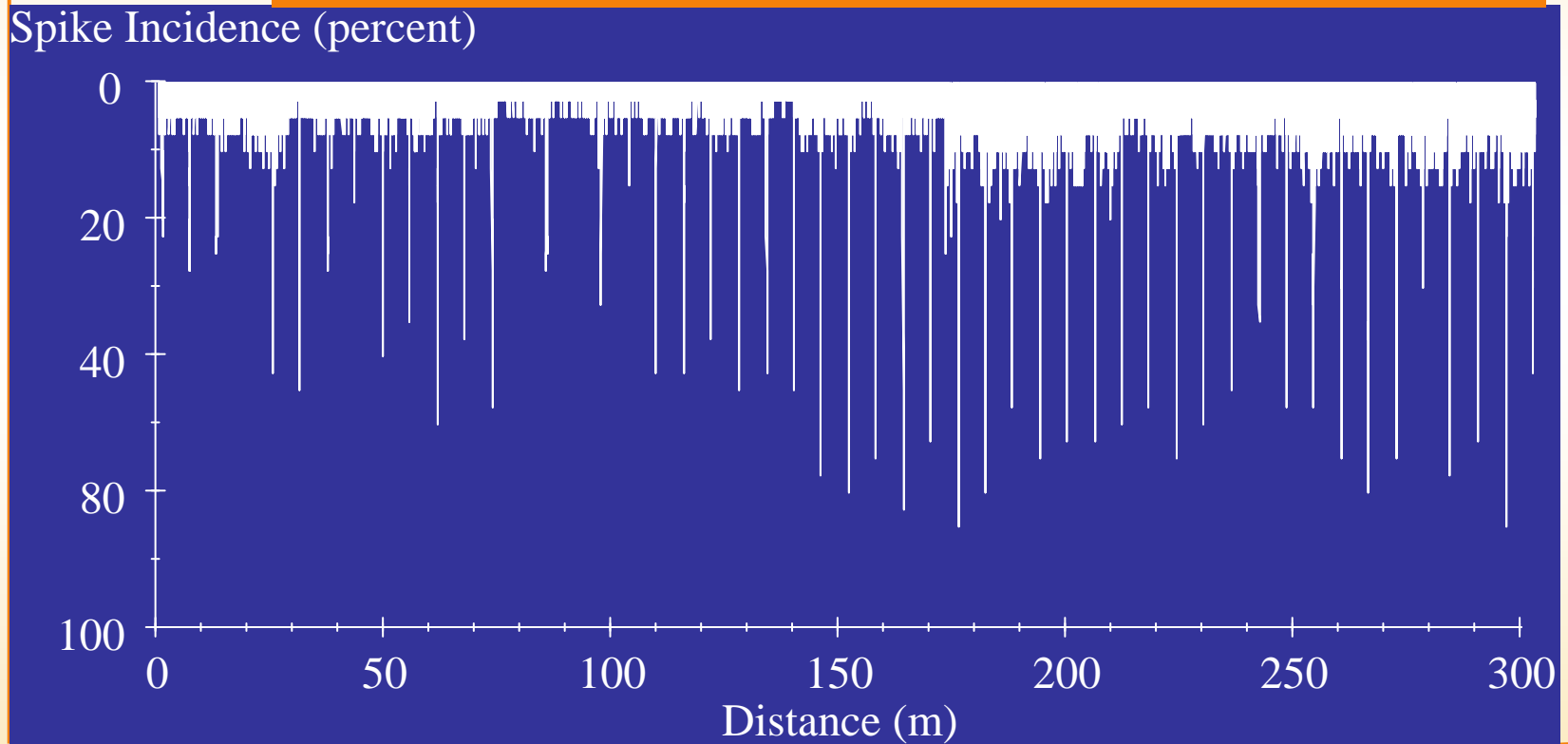
Filter with moving average anti-smoothing  
Normalize by RMS  
Search deepest dip by a threshold

"Spike" Profile



# Spike Incidence

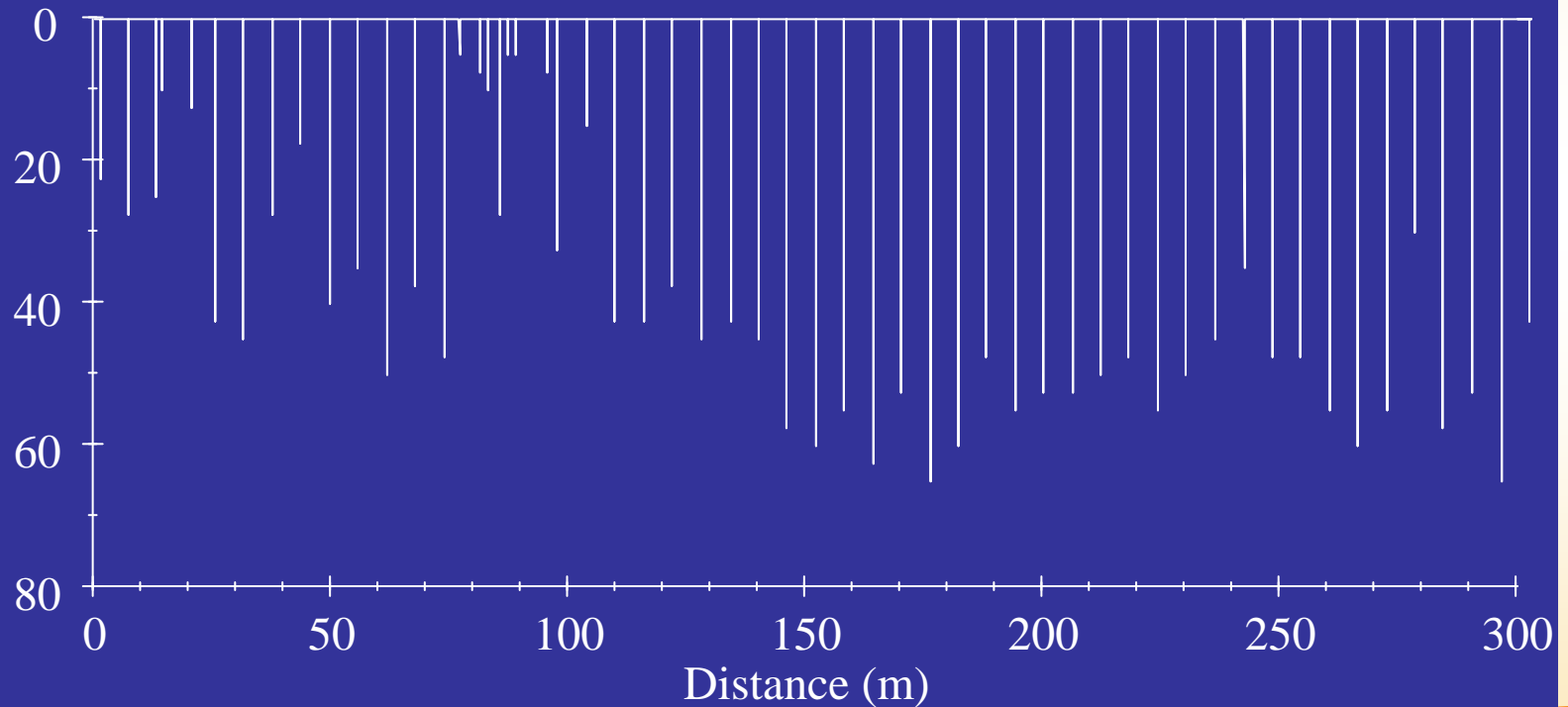
Assemble the dip count across the data set



# Weeded Spike Incidence

Weed/clear false hits  
Extract the joint locations

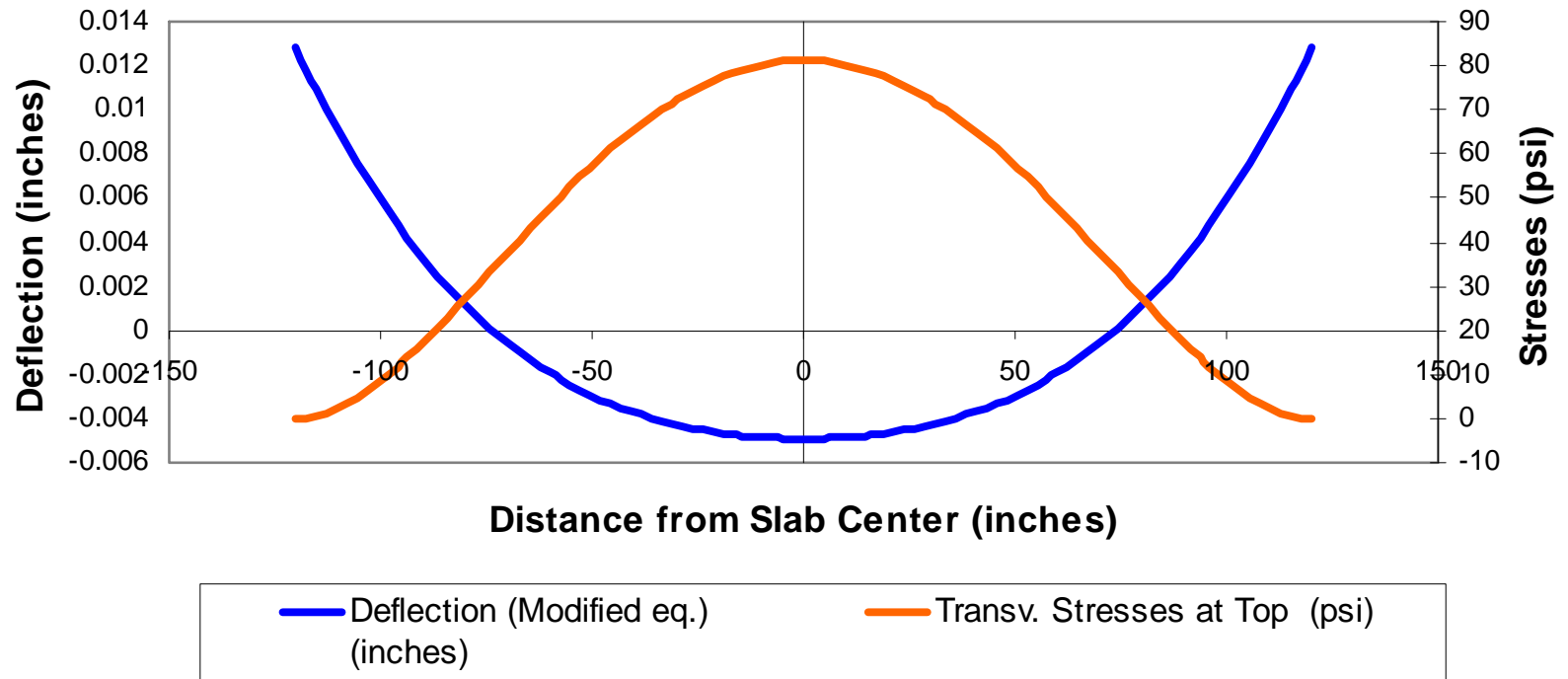
Weeded Spike Incidence (percent)



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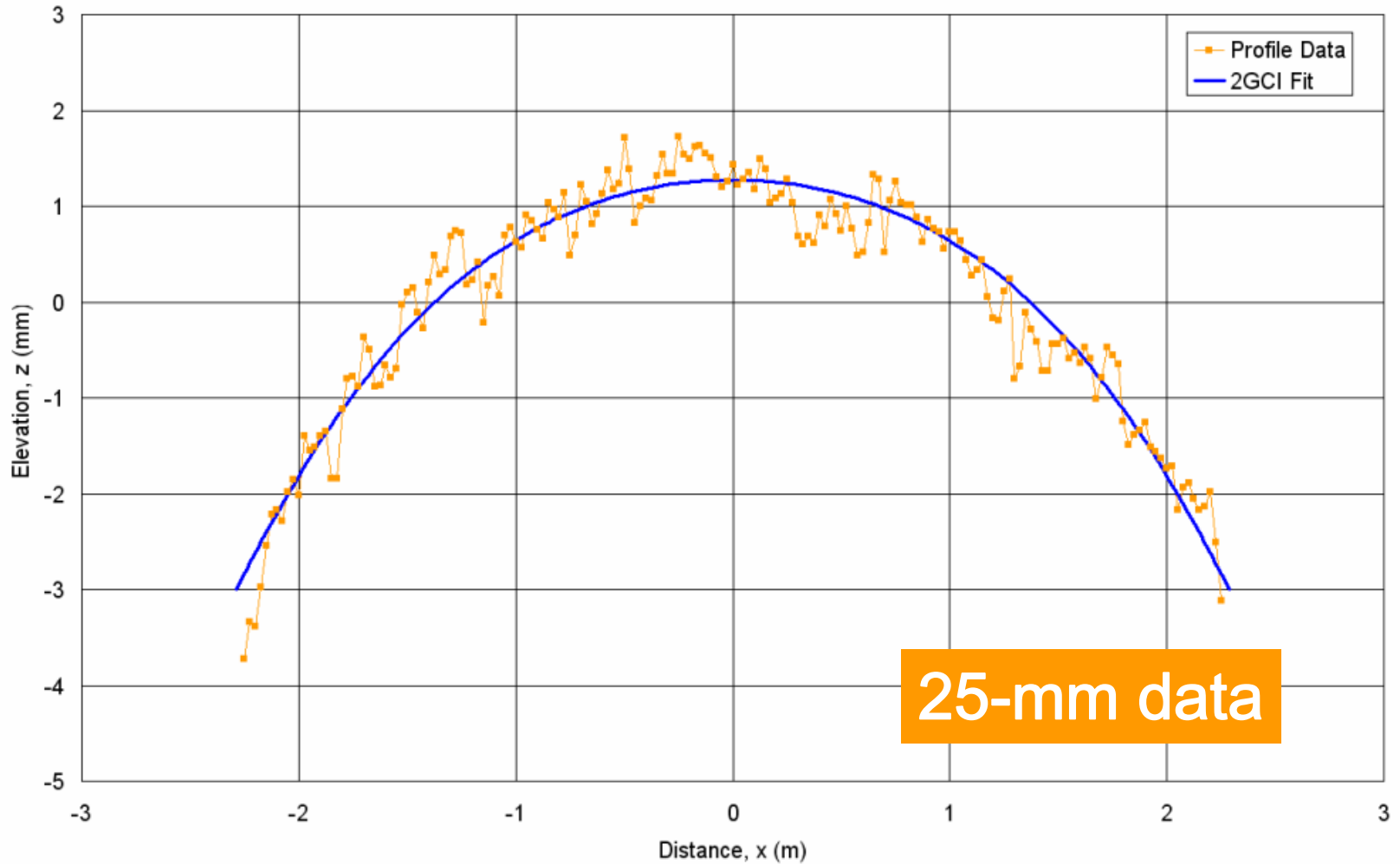
# Westergaard Curling Formula



## Adjusted Westergaard Curling Parameters

- Adjusted to overcome Westergaard assumptions
- Fit to actual slab deformation
- More fundamental than an arbitrary geometric function
- Fitted parameters:
  - Pseudo-radius of relative stiffness
  - Pseudo-strain gradient

## 2GCI Fit – Curled Down Slab



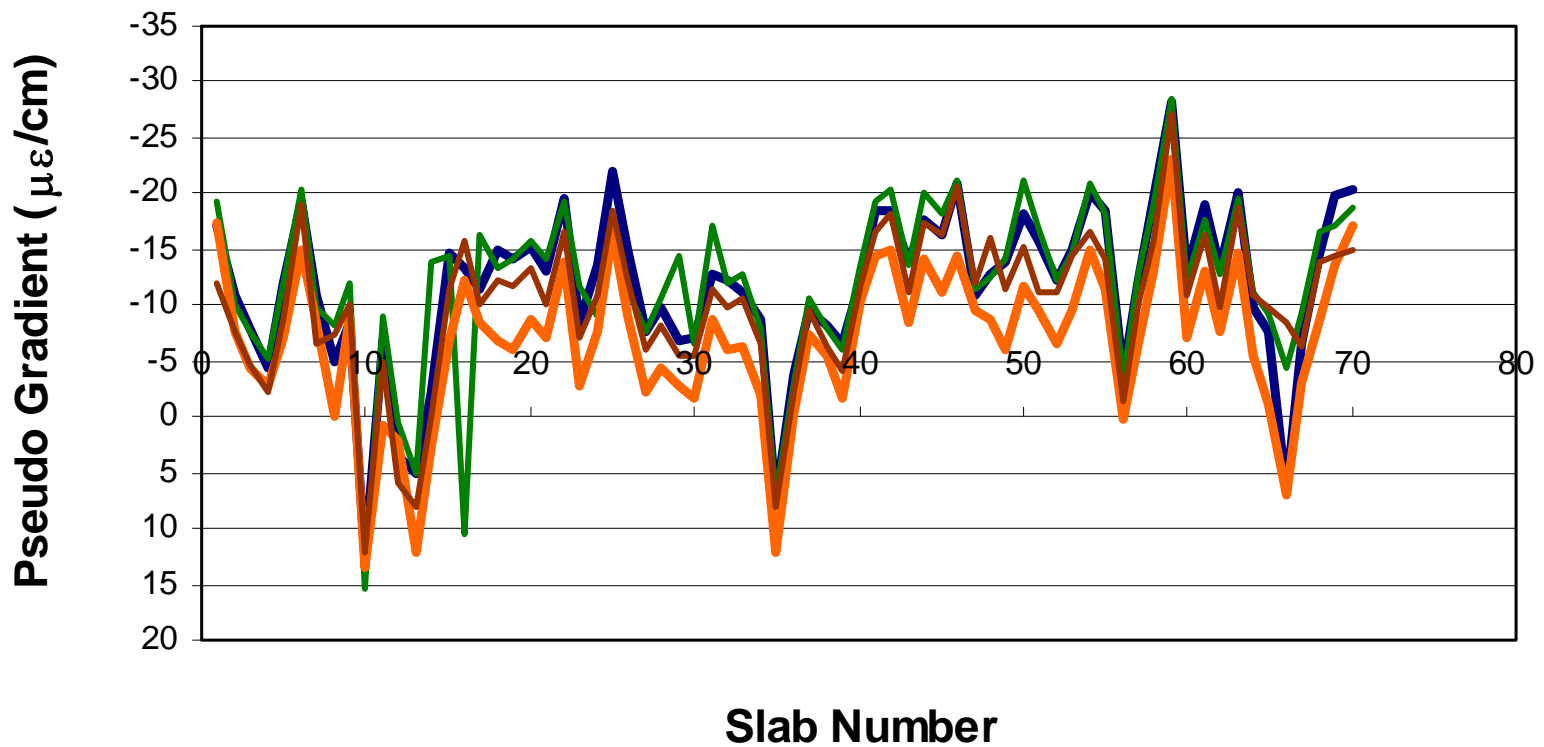
## 2GCI Computation

- **Isolate the individual slab segments**
- **De-trend and de-mean the profile segment**
- **Mask joints**
- **Define model parameters**
- **Perform nonlinear curve fitting**



# 2GCI Analysis

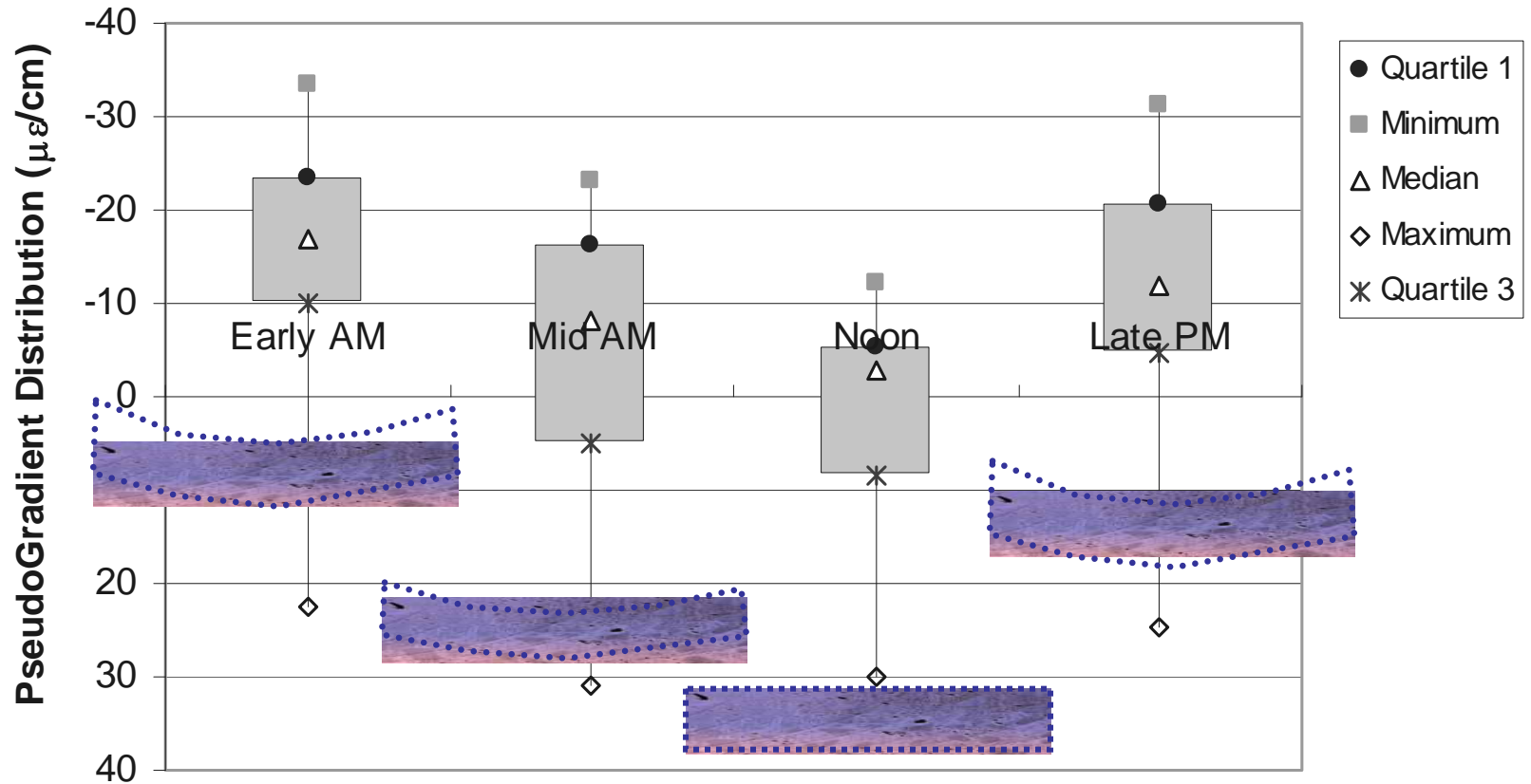
AZ\_001am - winter



— Early AM — Mid AM — Noon — Late PM

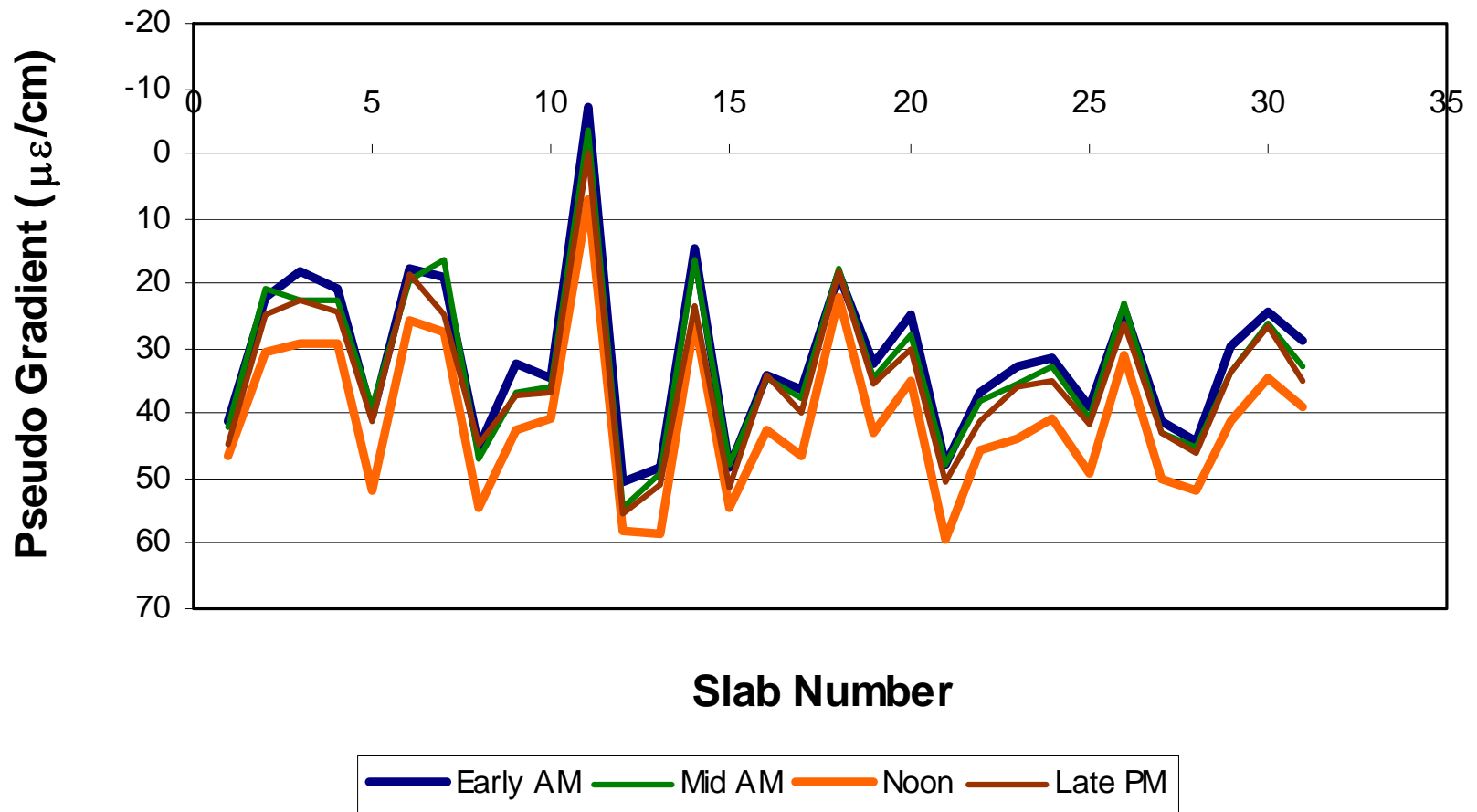
# 2GCI Analysis

AZ\_001am - winter



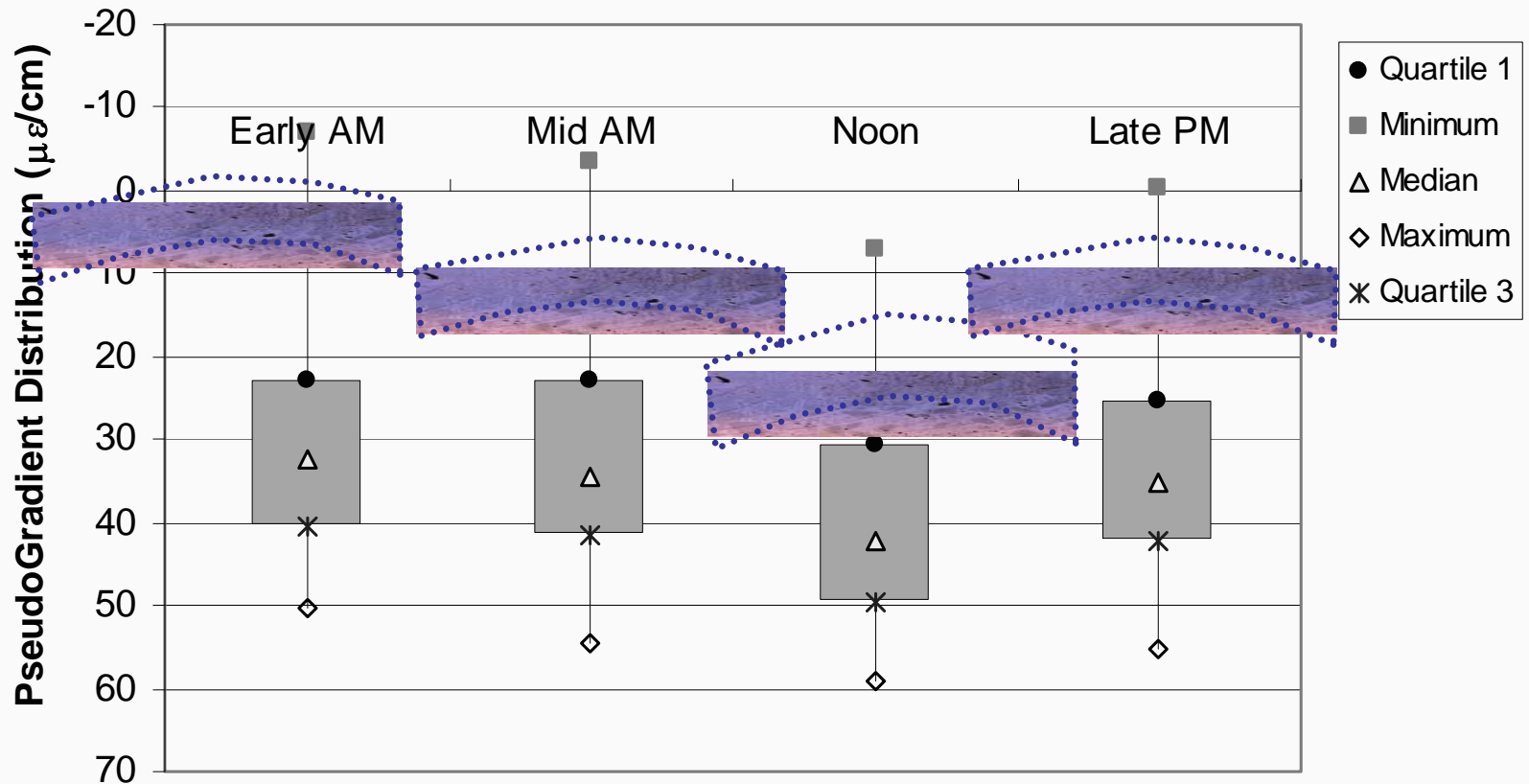
# 2GCI Analysis

MN\_046a - summer

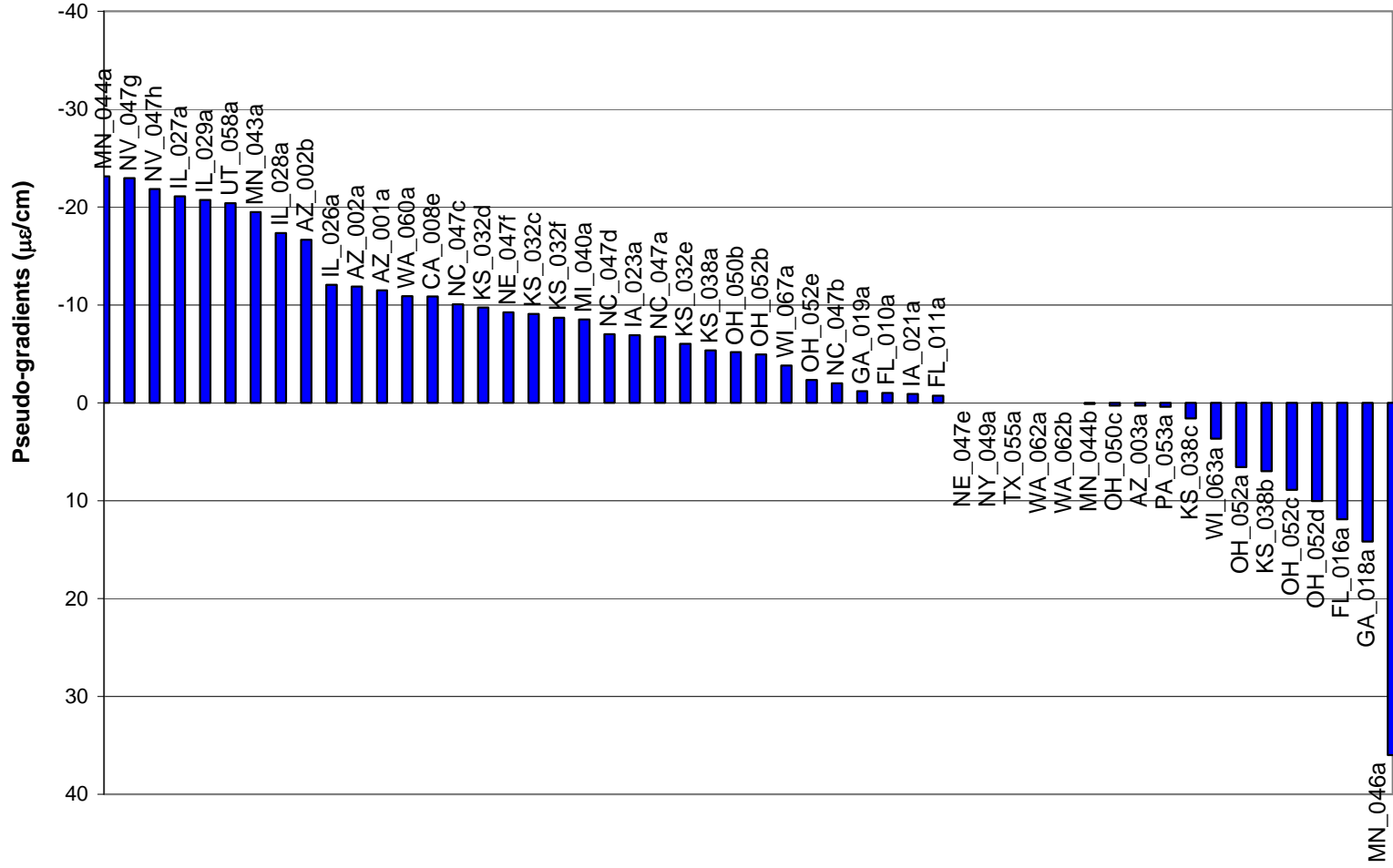


# 2GCI Analysis

MN\_046a - summer



# Mean Curvatures

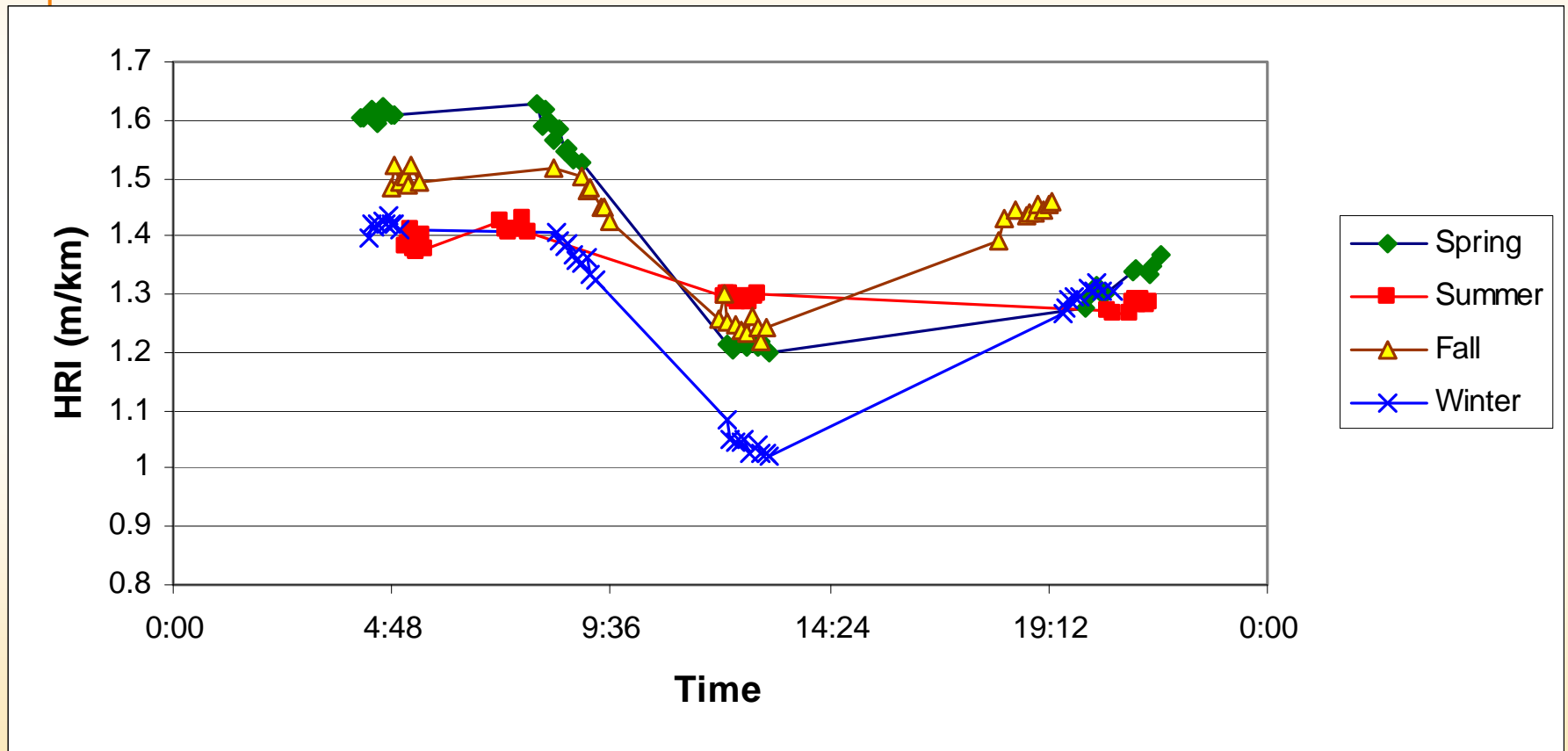


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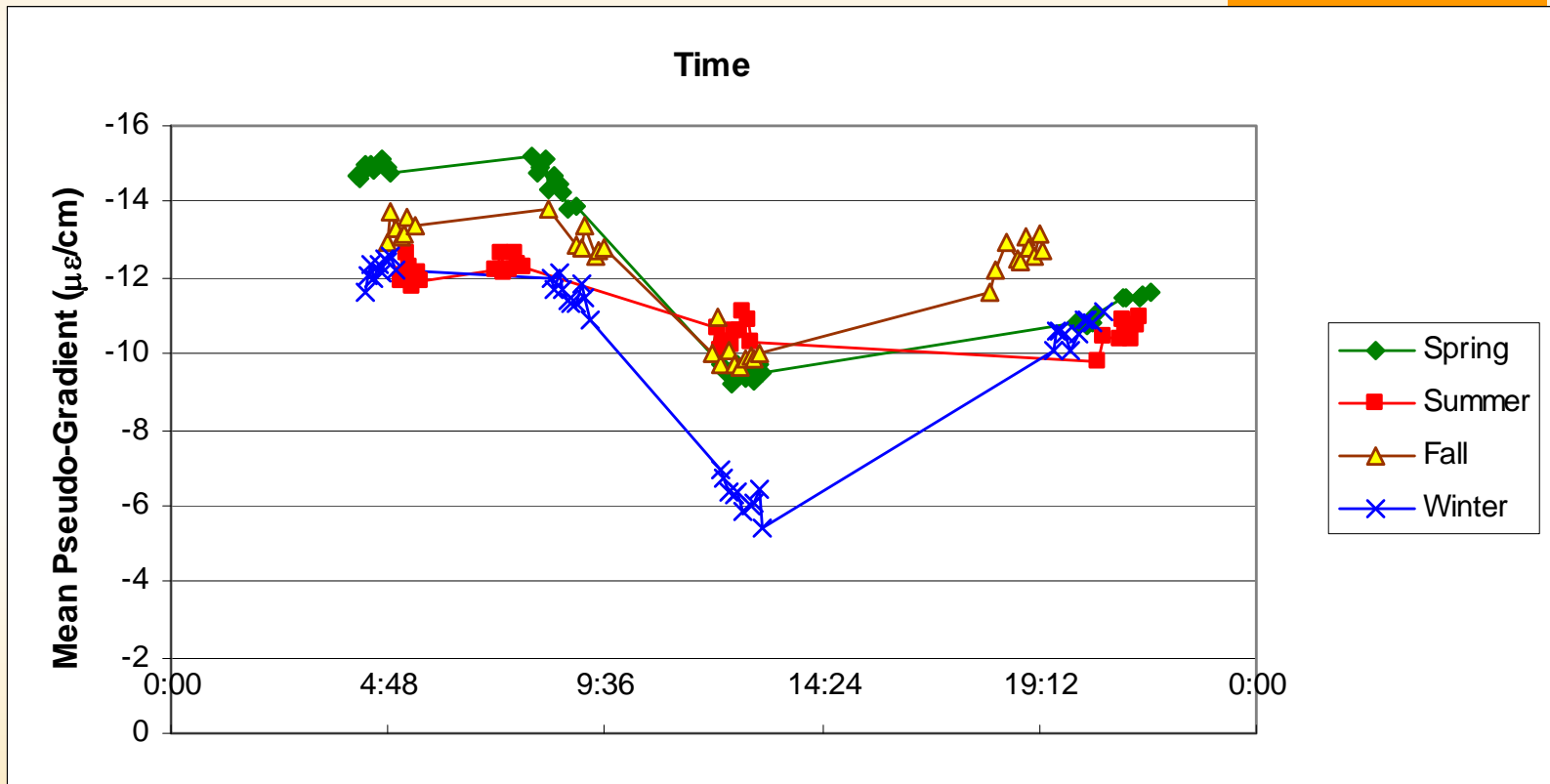
# 2GCI vs Roughness

AZ\_001m



# 2GCI vs Roughness

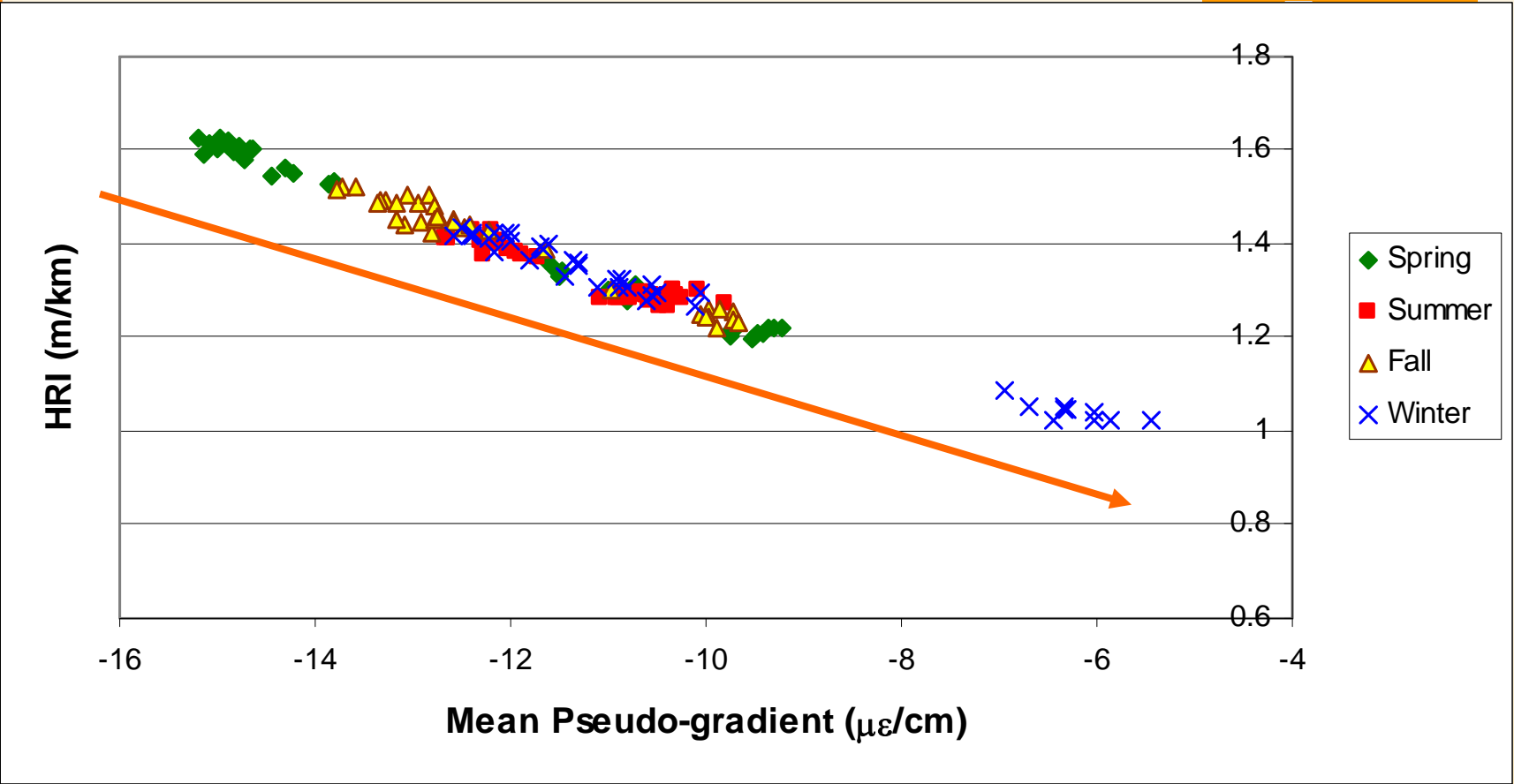
AZ\_001m



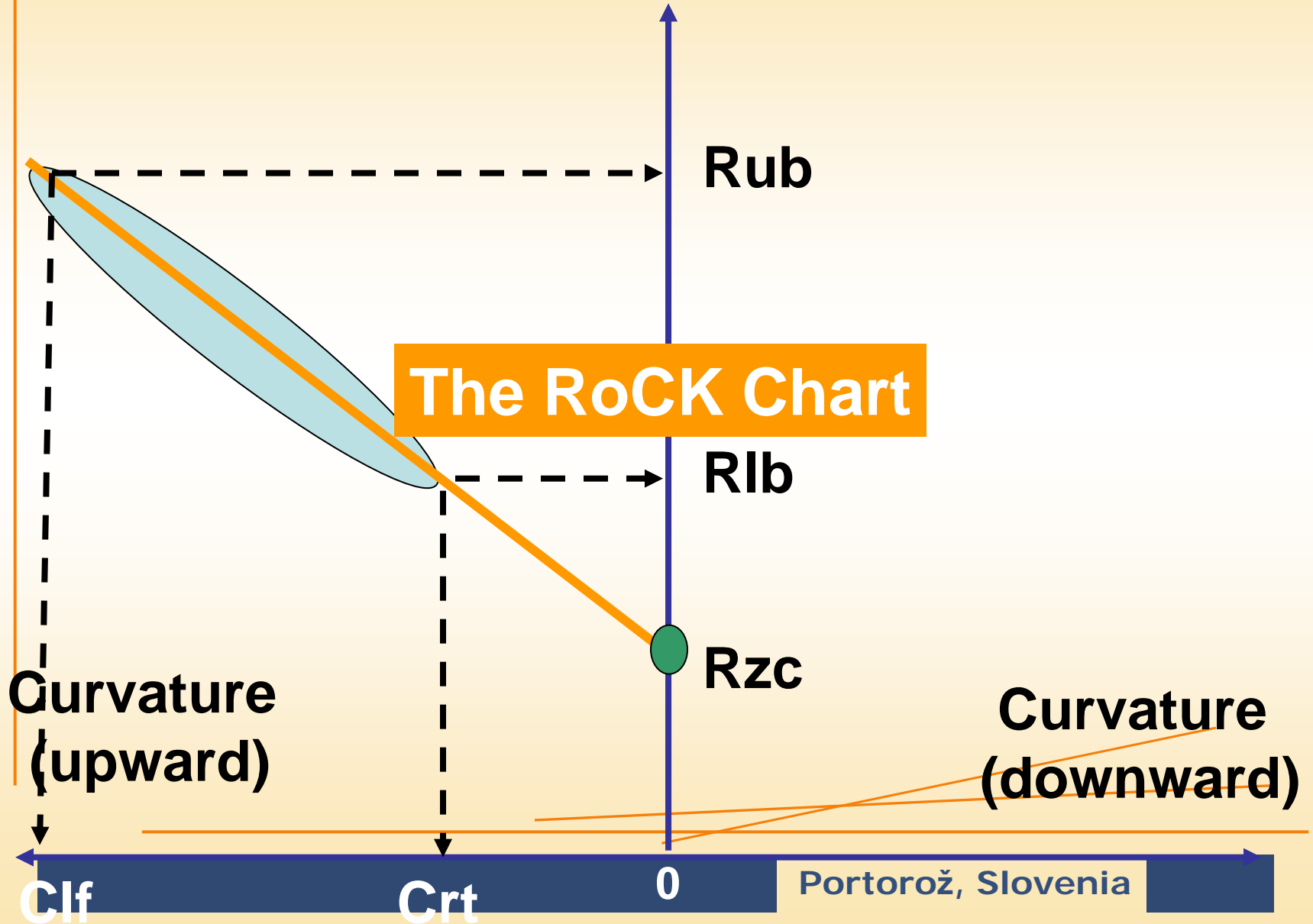


2GCI vs Roughness

AZ 001m



# Roughness



# Roughness Decomposition

$R_{ub}$

Curvature-related Roughness

$R_{lb}$

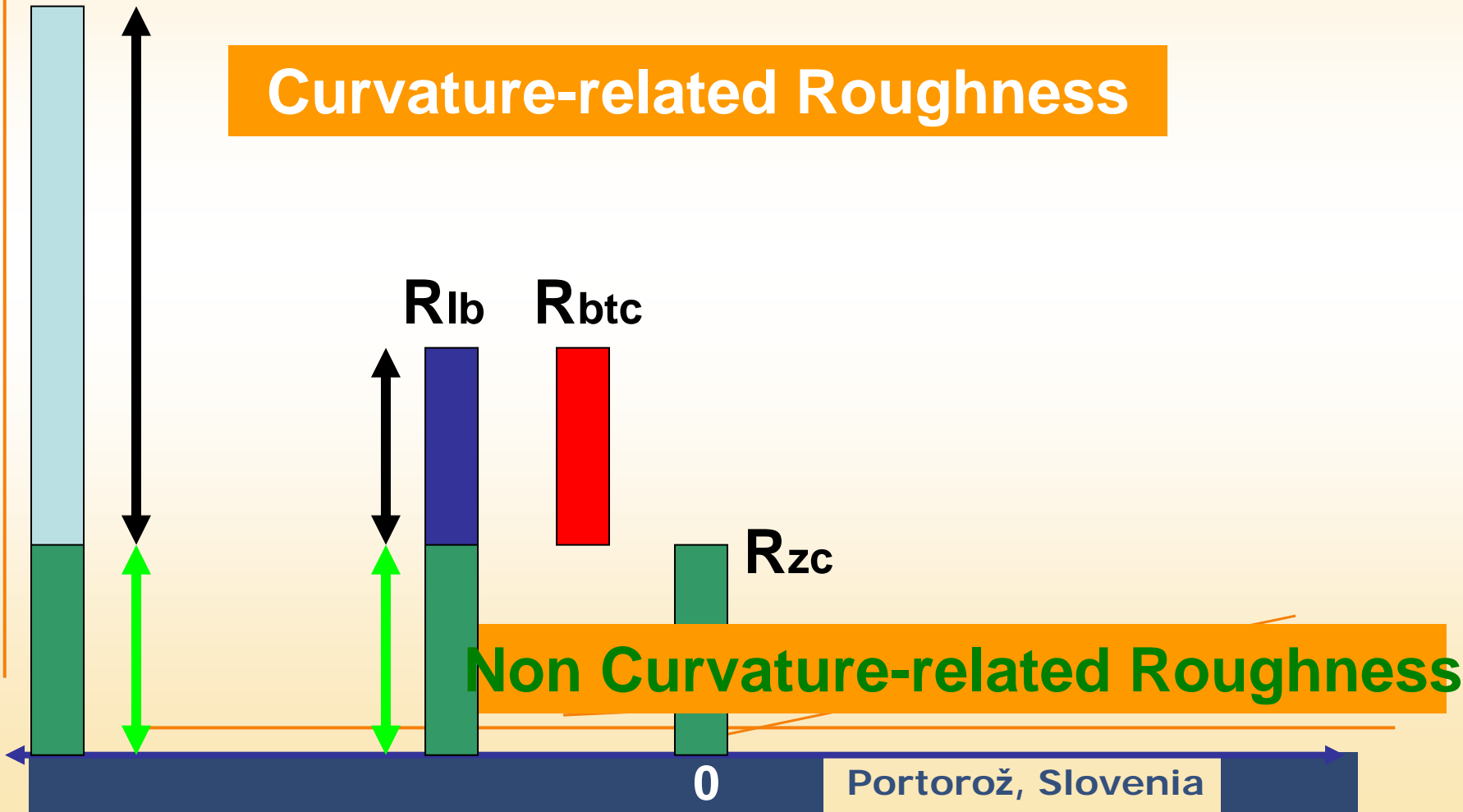
$R_{btc}$

$R_{zc}$

Non Curvature-related Roughness

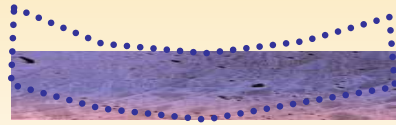
0

Portorož, Slovenia



# Roughness

TYPE I-A Sites



$S_{rc} < 0$   
 $R_{btc} > 0$

Rub

Curled up  
Curvature dominates  
roughness

Rlb

Rzc

Curvature  
(downward)

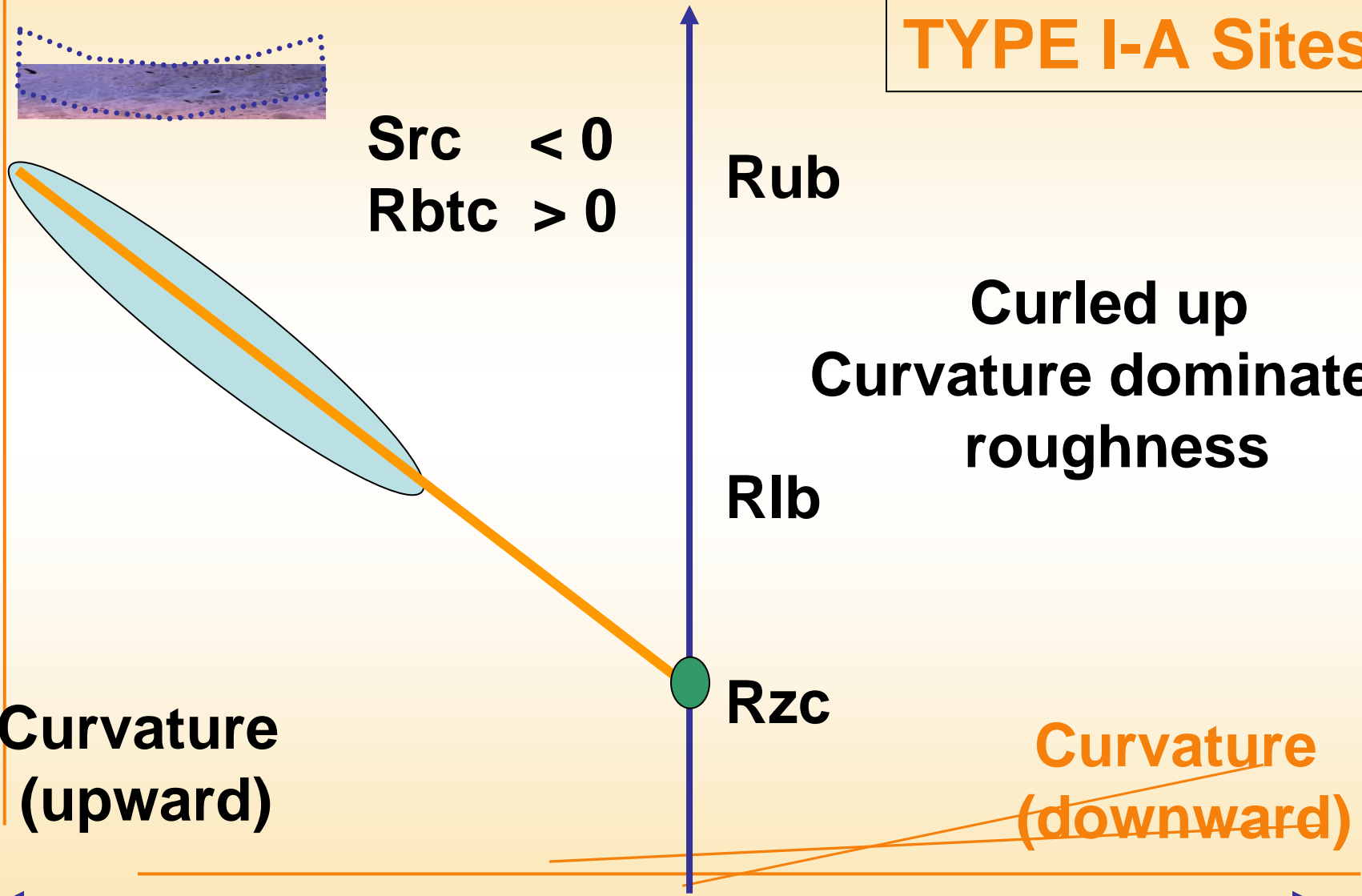
Curvature  
(upward)

Clf

Crt

0

Portorož, Slovenia

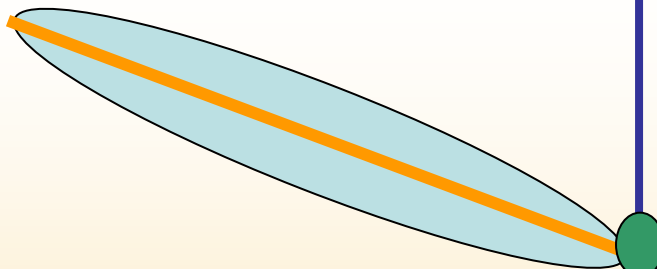
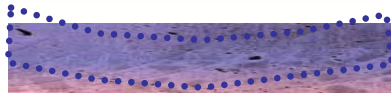


# Roughness

TYPE I-B Sites

$S_{rc} < 0$   
 $R_{btc} \sim 0$

Curled up mildly  
Curvature affects  
roughness



$R_{zc}$   $R_{lb}$

Curvature  
(upward)

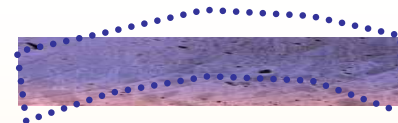
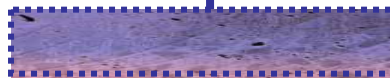
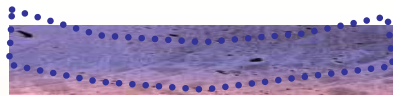
Curvature  
(downward)

# Roughness

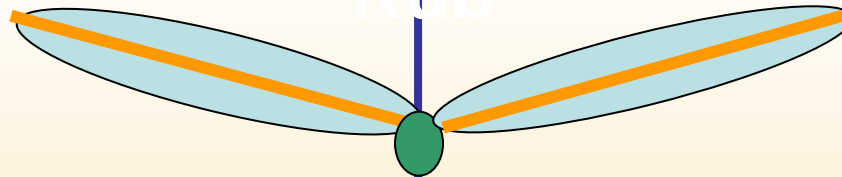
## TYPE II Sites

Curled up and down  
Curvature affects  
Roughness mildly

$S_{rc} < 0$   
 $R_{btc} \sim 0$



$R_{ub}$



$R_{zc}$   $R_{lb}$

Curvature  
(upward)

Curvature  
(downward)

$C_{lf}$

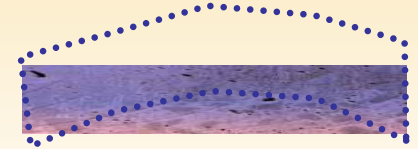
$C_{rt}$

Portorož, Slovenia

# Roughness

## TYPE III-A Sites

**Curled down**  
**Curvature dominates**  
**roughness**



**Rub**

$Src > 0$

**Rzc**

**Curvature**  
**(upward)**

**Curvature**  
**(downward)**

0

Portorož, Slovenia

**Clf**

**Crt**

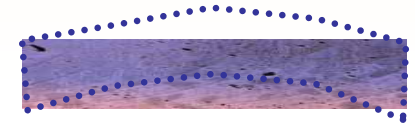


# Roughness

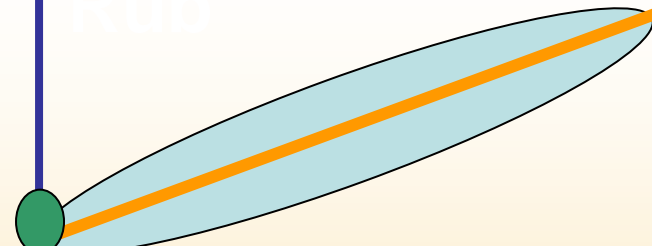
## TYPE III-B Sites

Curled down mildly  
Curvature affects  
roughness

$$S_{rc} > 0$$
$$R_{btc} \sim 0$$



$R_{ub}$



Curvature  
(upward)

$R_{zc}$

$R_{lb}$

Curvature  
(downward)

$C_{lf}$

$C_{rt}$

Portorož, Slovenia



## **Bolivian Project**

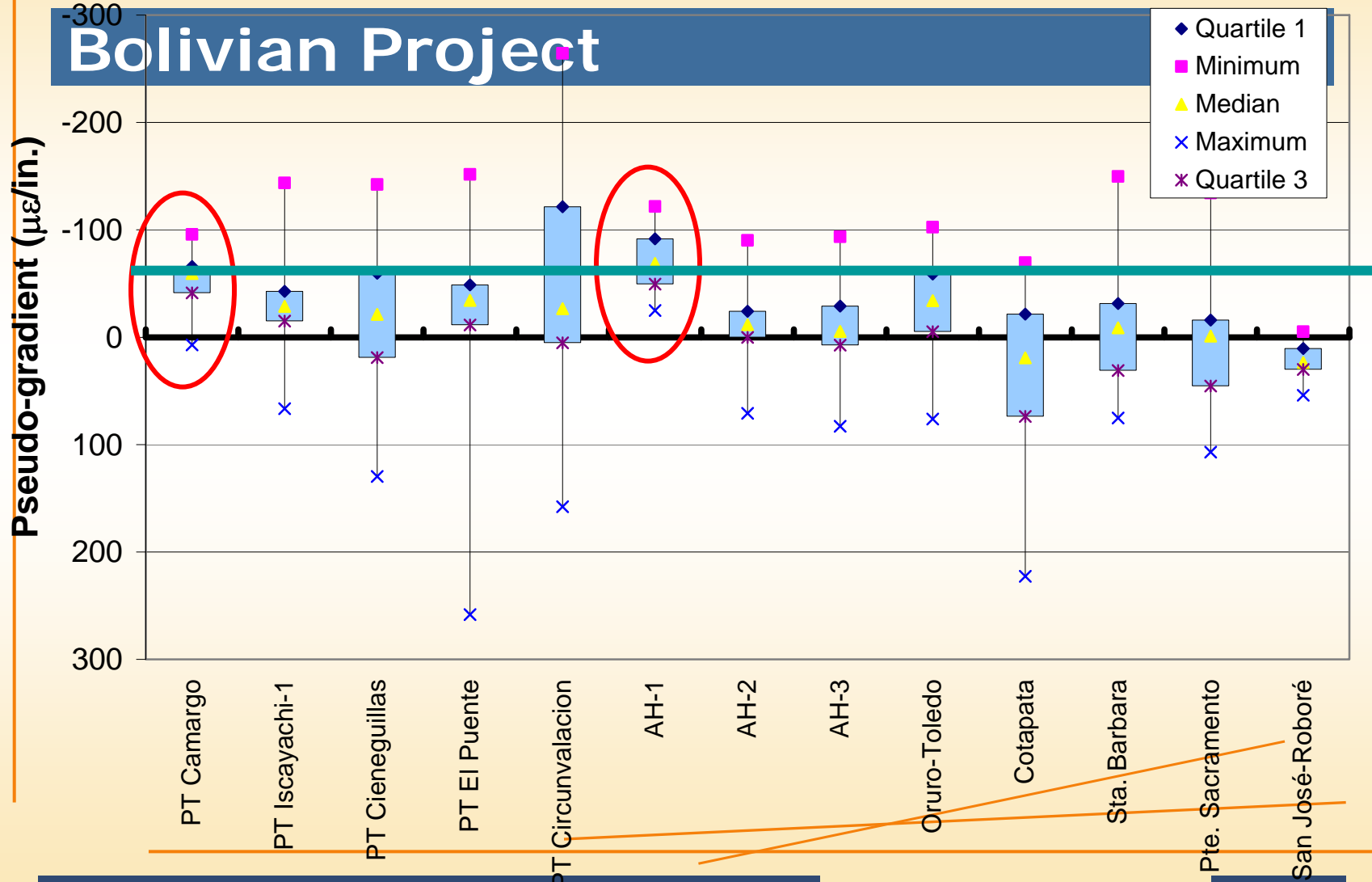
- Two-lane undivided JCP**
- Mountainous terrain with moderate fills and cuts**
- 24-ft wide, 12-ft joint spacing**
- 8-inch slab on 6-inch granular base**
- Local climate is arid with rains from December to March**
- Drastic overnight temperature drops**

## Bolivian Project

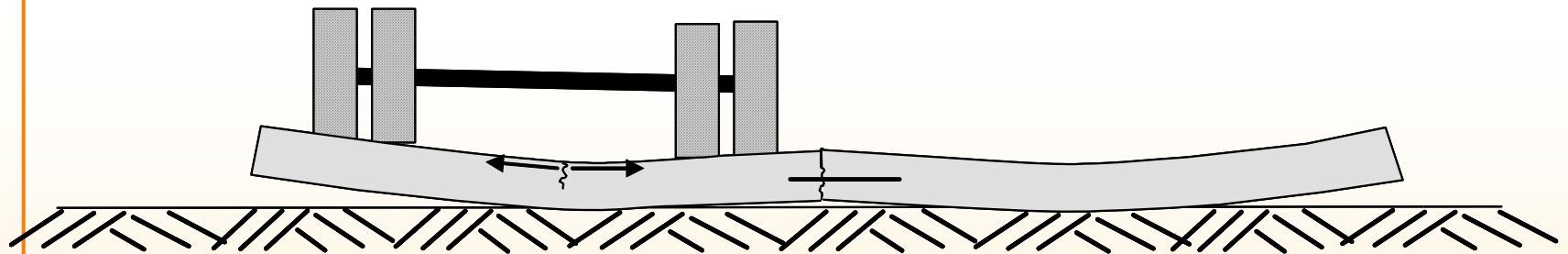
- Low relative humidity and extreme temperatures
- Mix with a relatively high water cement ratio, high CTE aggregate, and inadequate curing techniques.
- Longitudinal cracks at the center of the slab in both travel directions after the first winter

Pavement Section

Bolivian Project



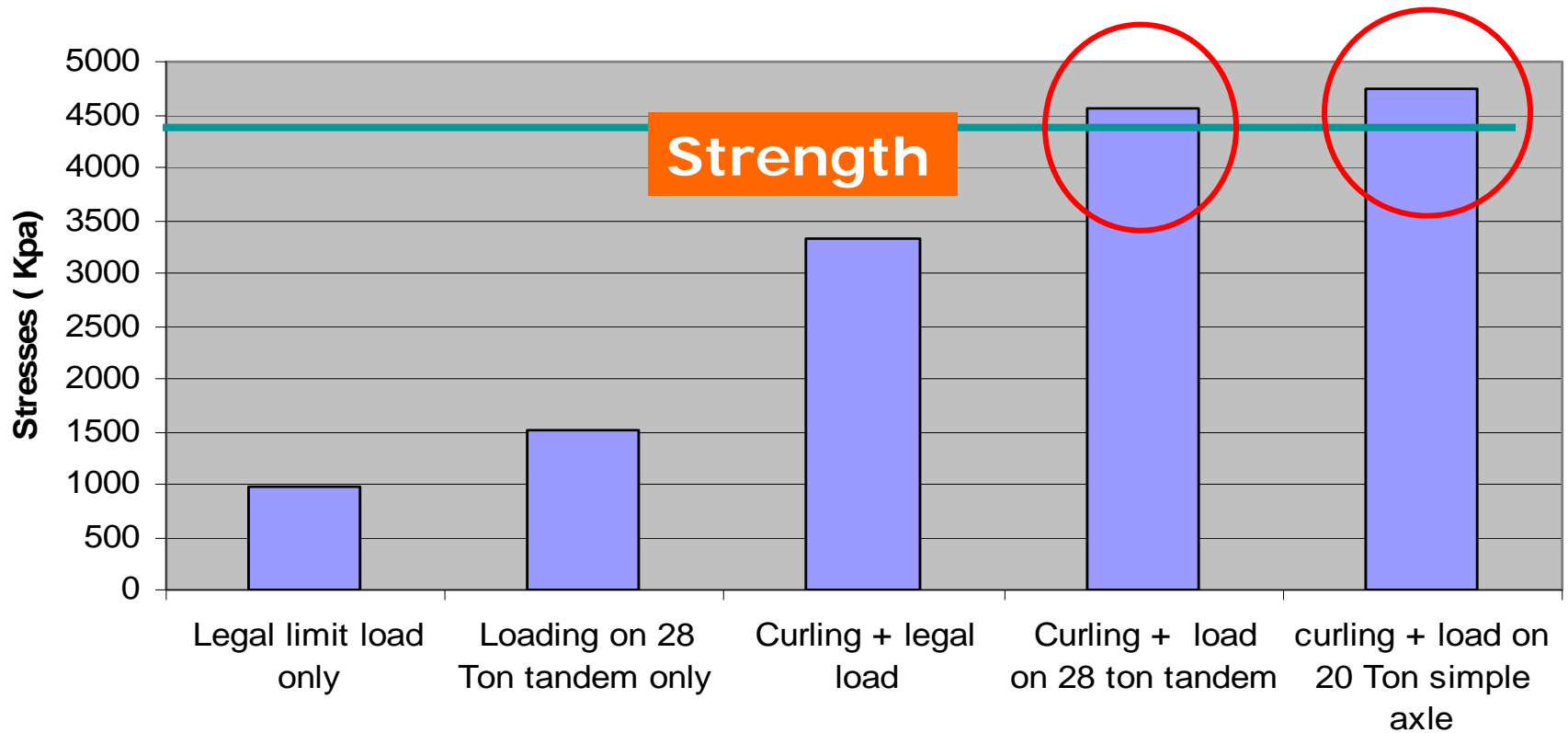
# Bolivian Project



# Bolivian Project

## FEM Analysis

### Effect of curling and loading-current geometry



## The Implications...

- **What's timing to measure roughness for a pavement acceptance testing?**
- **What's the best practice to avoid curl and warp?**
- **What's the best time to grind the pavements to improve smoothness?**

## Tools you can use...

- **New, robust profile synchronization and joint identification techniques**
- **Invention of 2GCI to better characterize slab curvature**
- **New, effective slab curvature analysis framework**
- **RoCK System to assess curvature's impact on roughness**

## Acknowledgement

- **US FHWA Sponsorship**
- **Co-authors:**
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  - David Merritt, P.E., M.S., The Transtec Group, Inc., USA
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