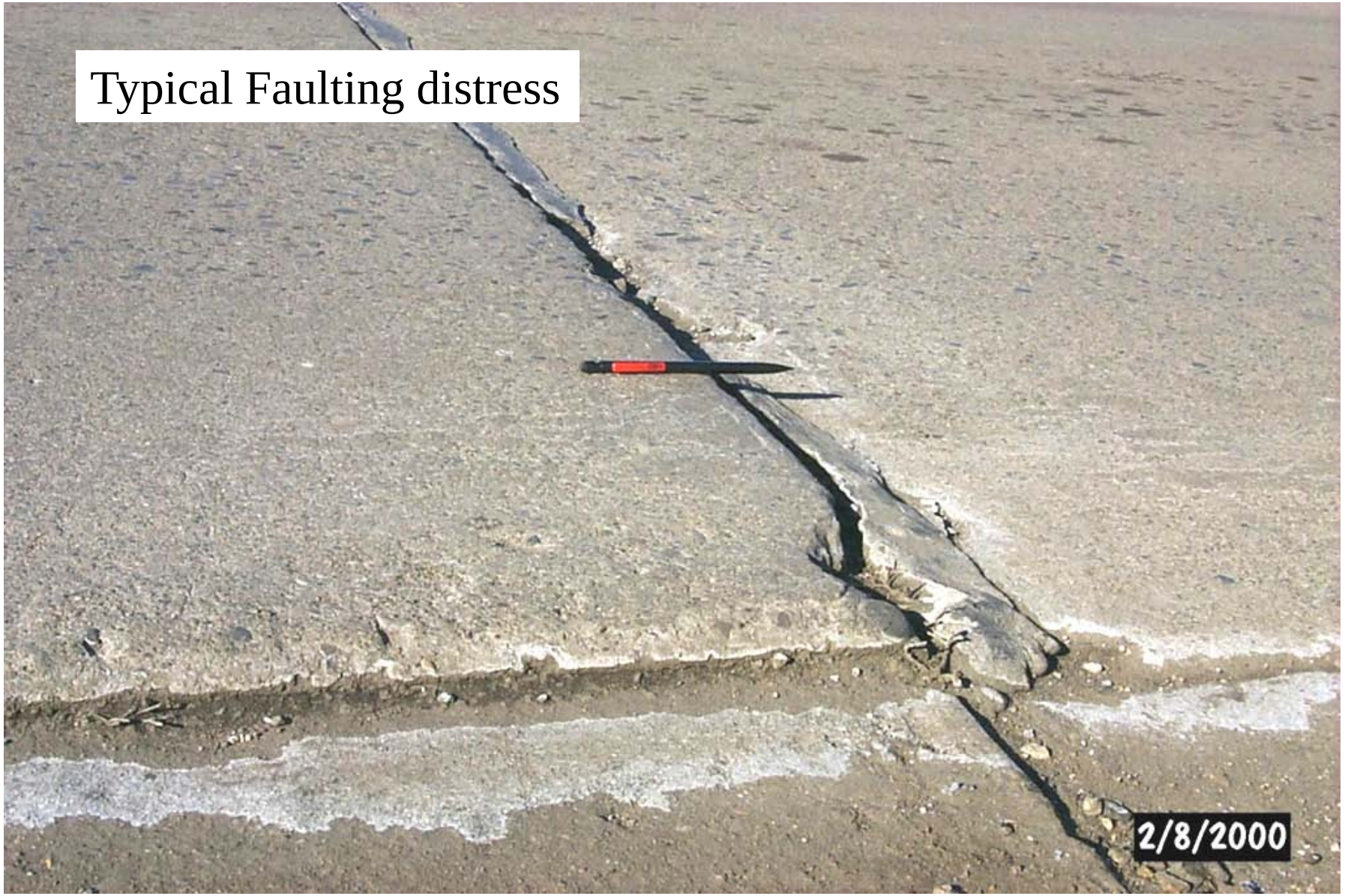
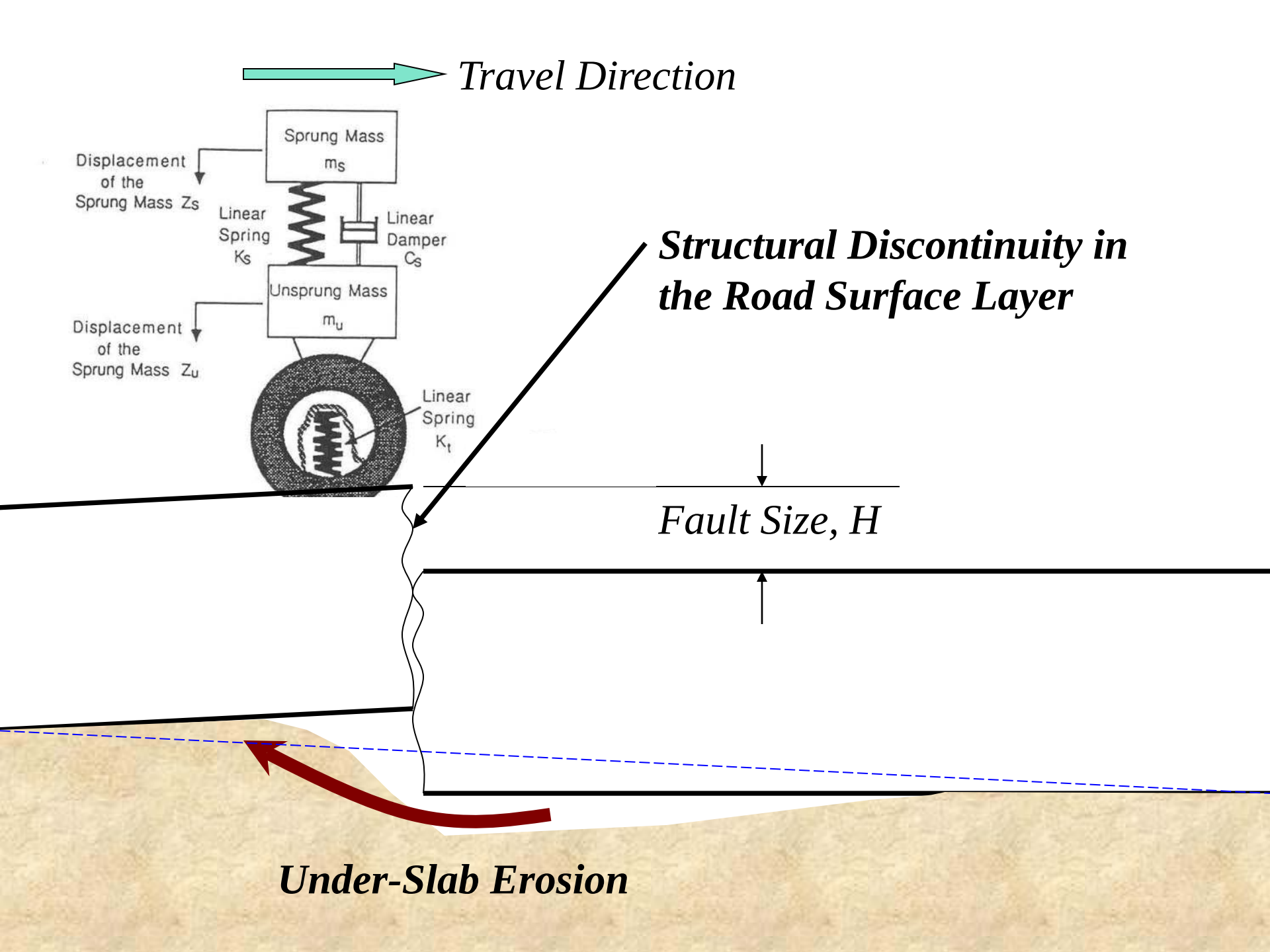
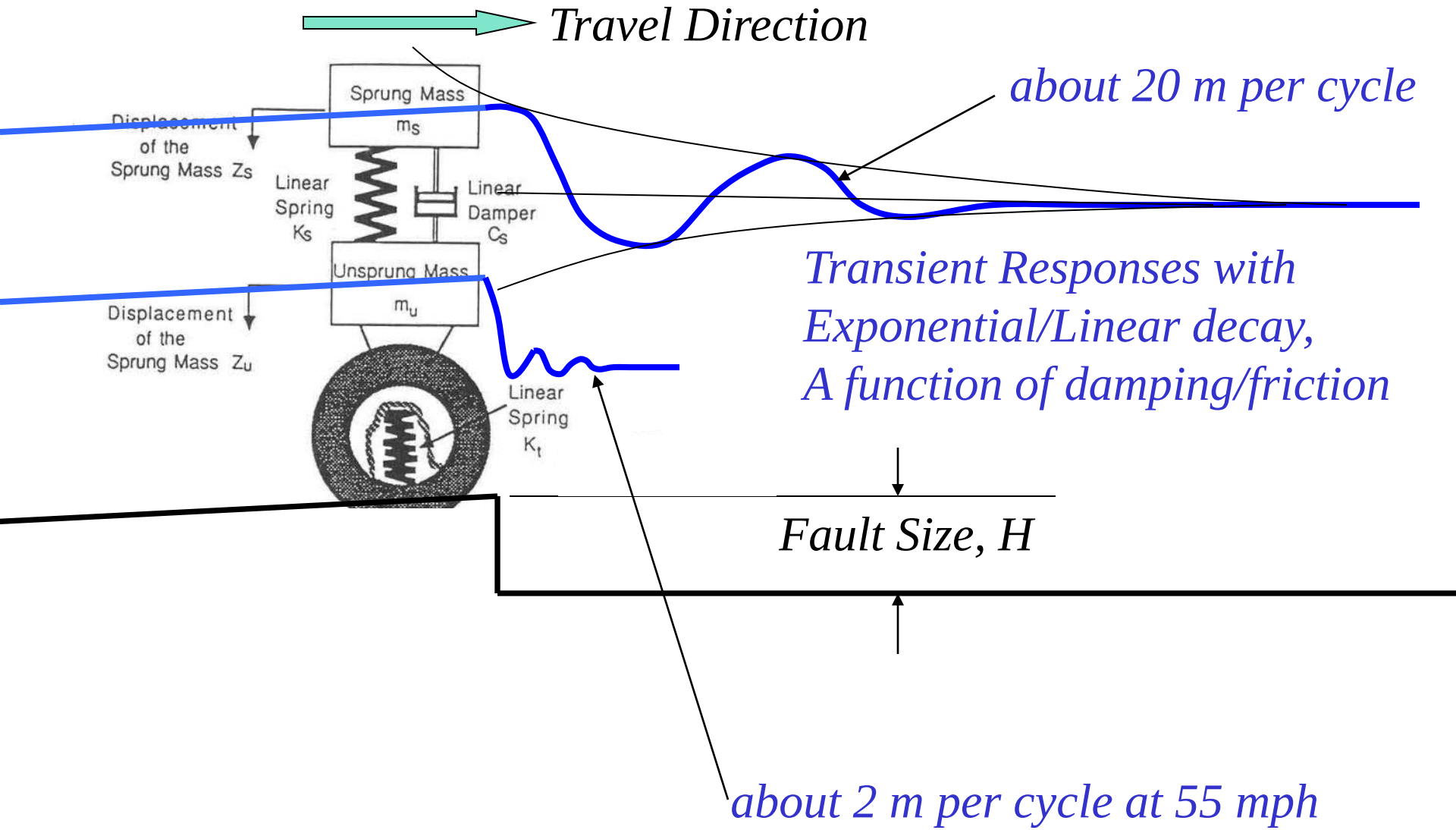
EVALUATING DOWEL EFFECTIVENESS WITH FAULTING DATA FROM RAPID PROFILERS

Christopher R. Byrum, Ph.D., P.E.
Soil & Materials Engineers, Inc.
Plymouth, MI Office


Typical Faulting distress
2/8/2000


Typical Faulting distress
2/8/2000

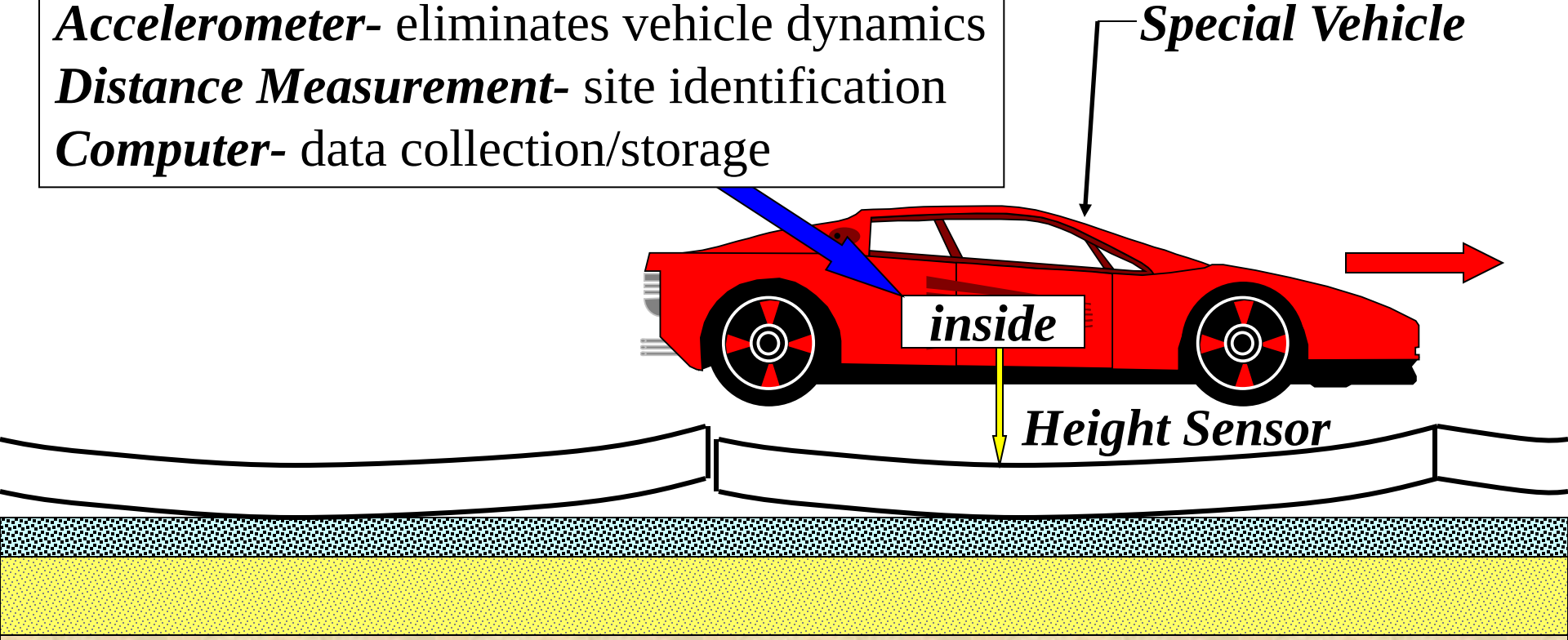

Travel Direction
Sprung Mass
m_S
Displacement of the Sprung Mass Z_S
Linear Spring K_S
Linear Damper C_S
Unsprung Mass
m_u
Displacement of the Sprung Mass Z_u
Linear Spring K_t
Structural Discontinuity in the Road Surface Layer
Fault Size, H
Under-Slab Erosion



Very Annoying Distress

HIGH-SPEED PROFILER

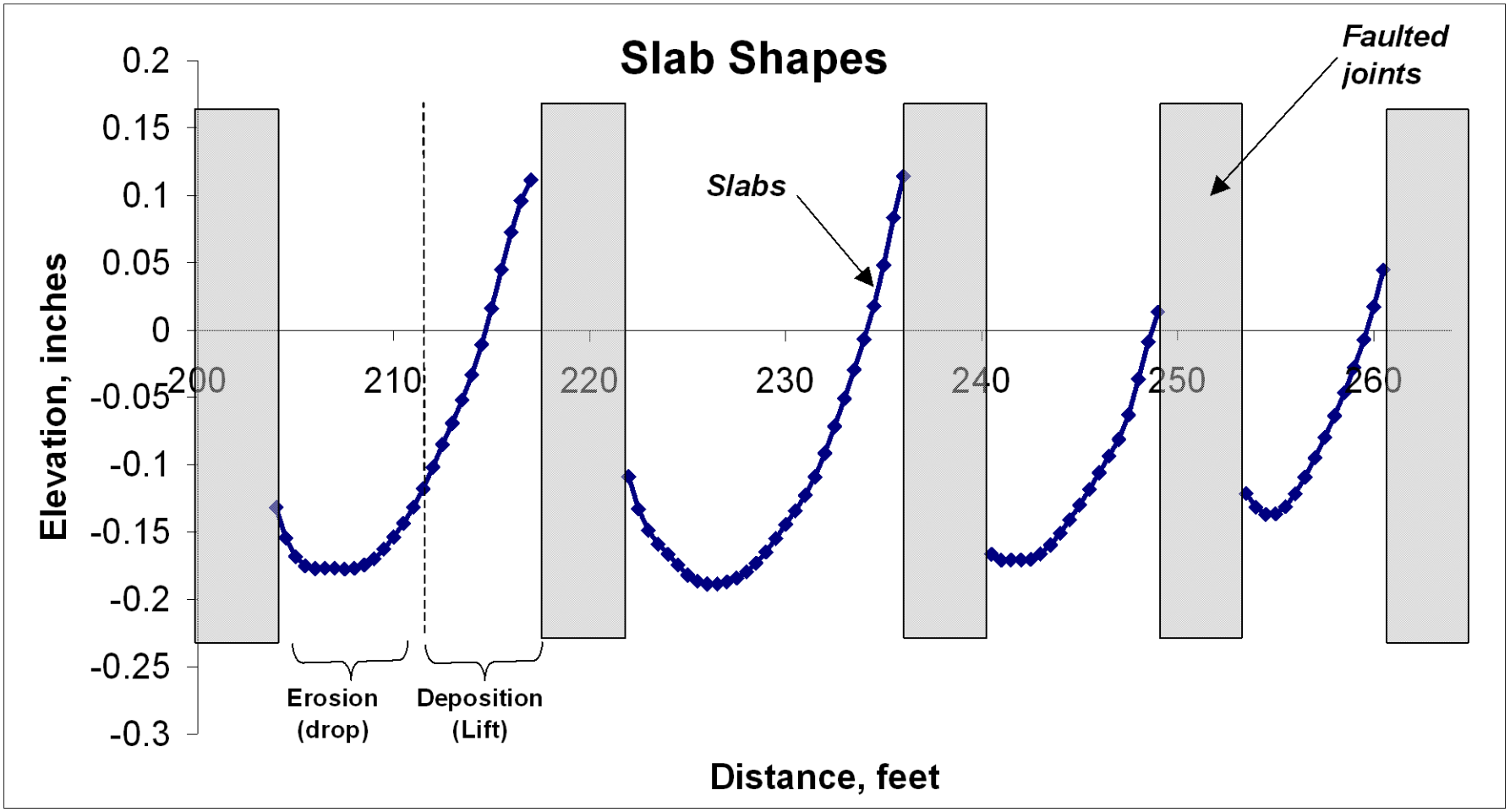
Accelerometer- eliminates vehicle dynamics
Distance Measurement- site identification
Computer- data collection/storage



Great Data!

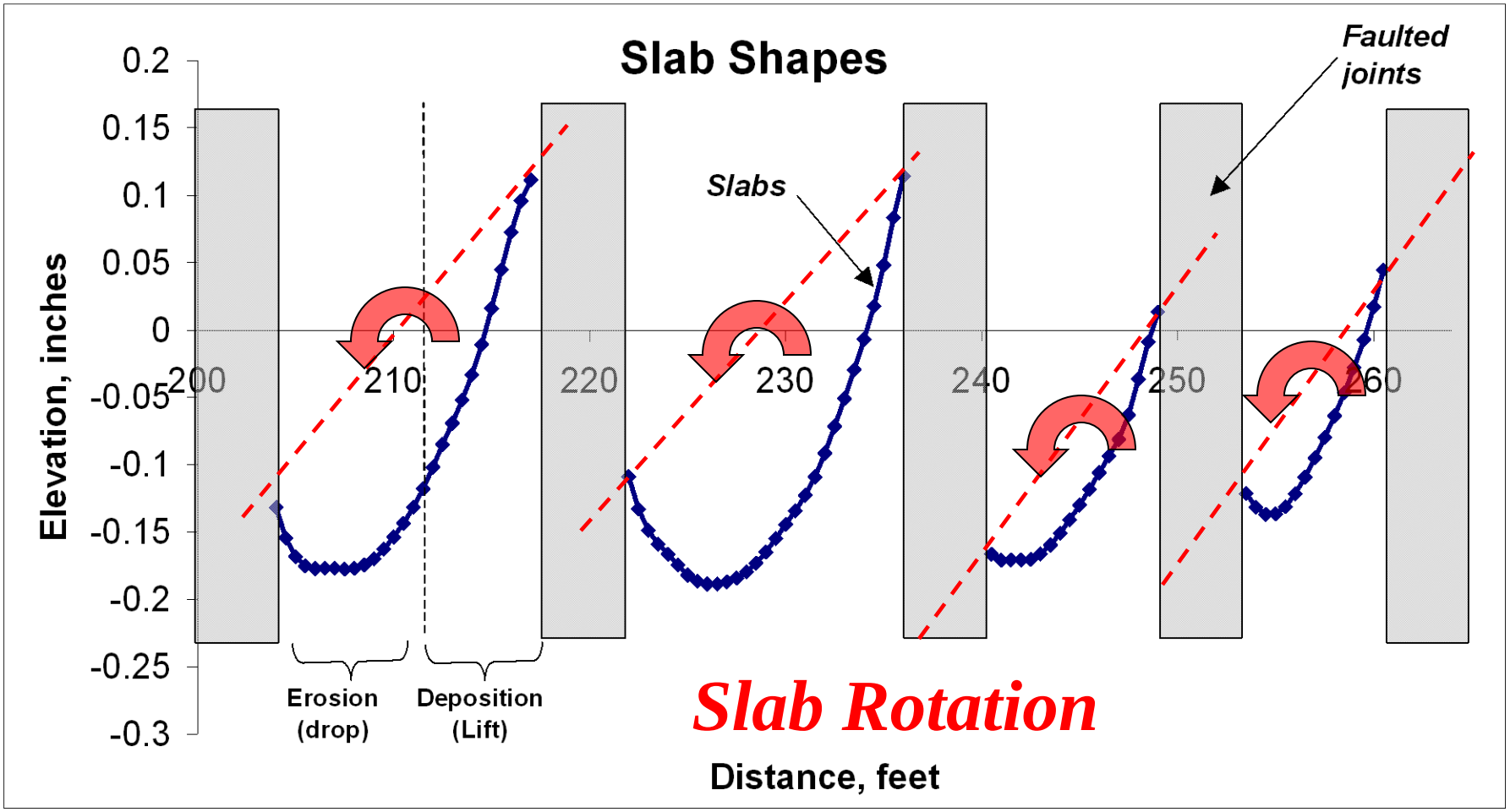
No Traffic Control Required!

Site 553009 7/13/94 7:48:52 PM



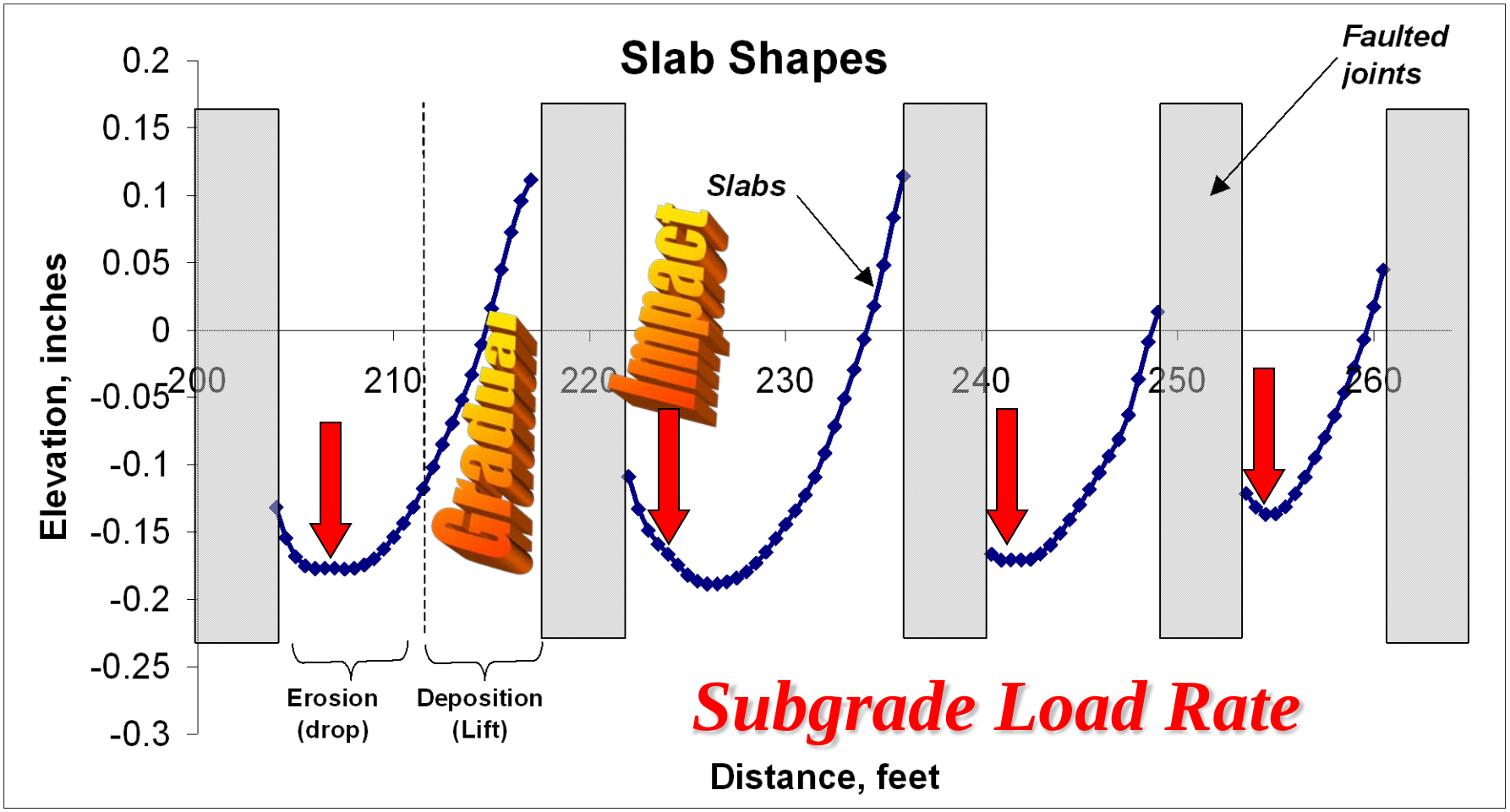
Traffic Direction

Site 553009 7/13/94 7:48:52 PM



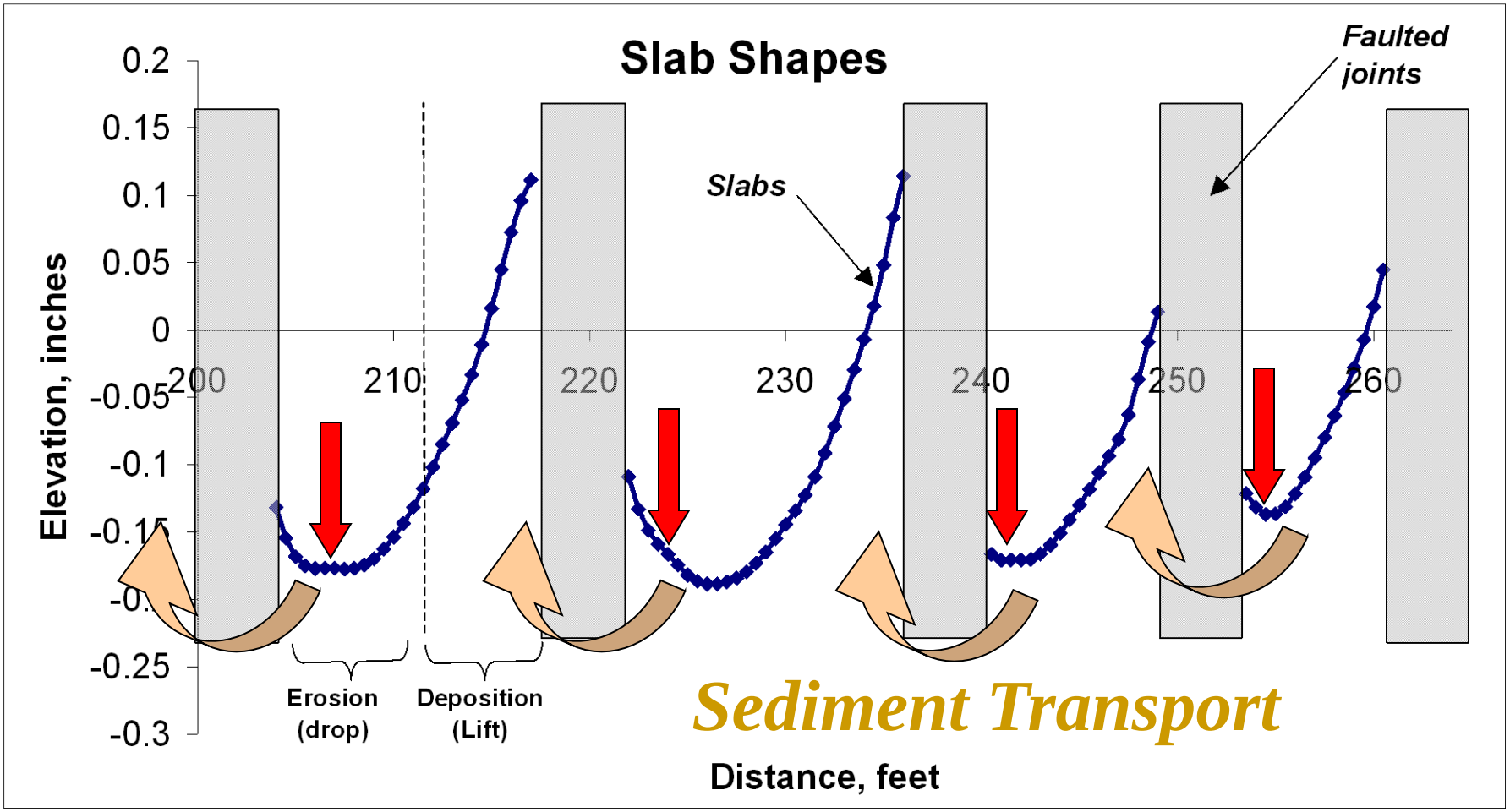
Traffic Direction

Site 553009 7/13/94 7:48:52 PM



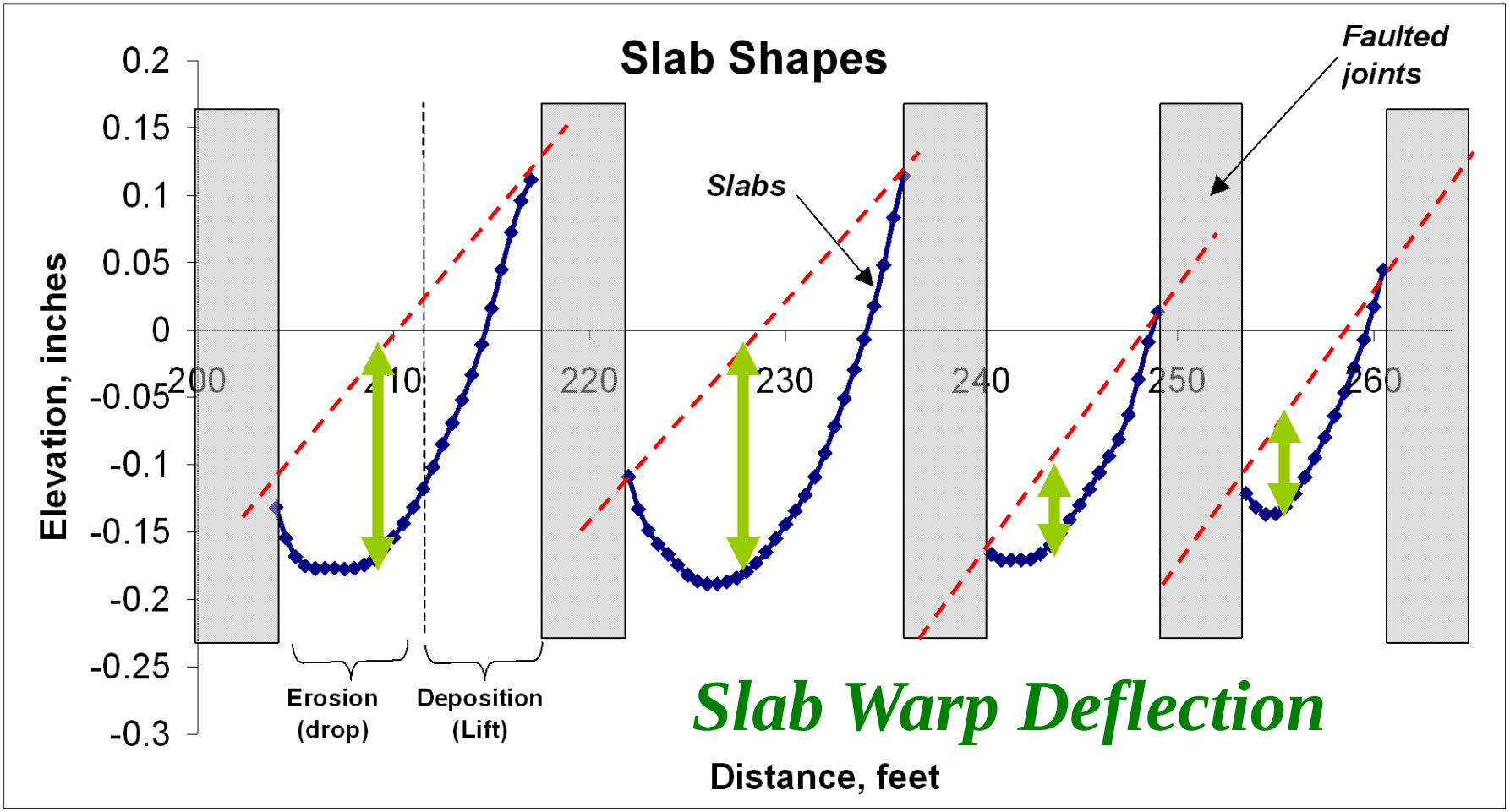
Traffic Direction

Site 553009 7/13/94 7:48:52 PM

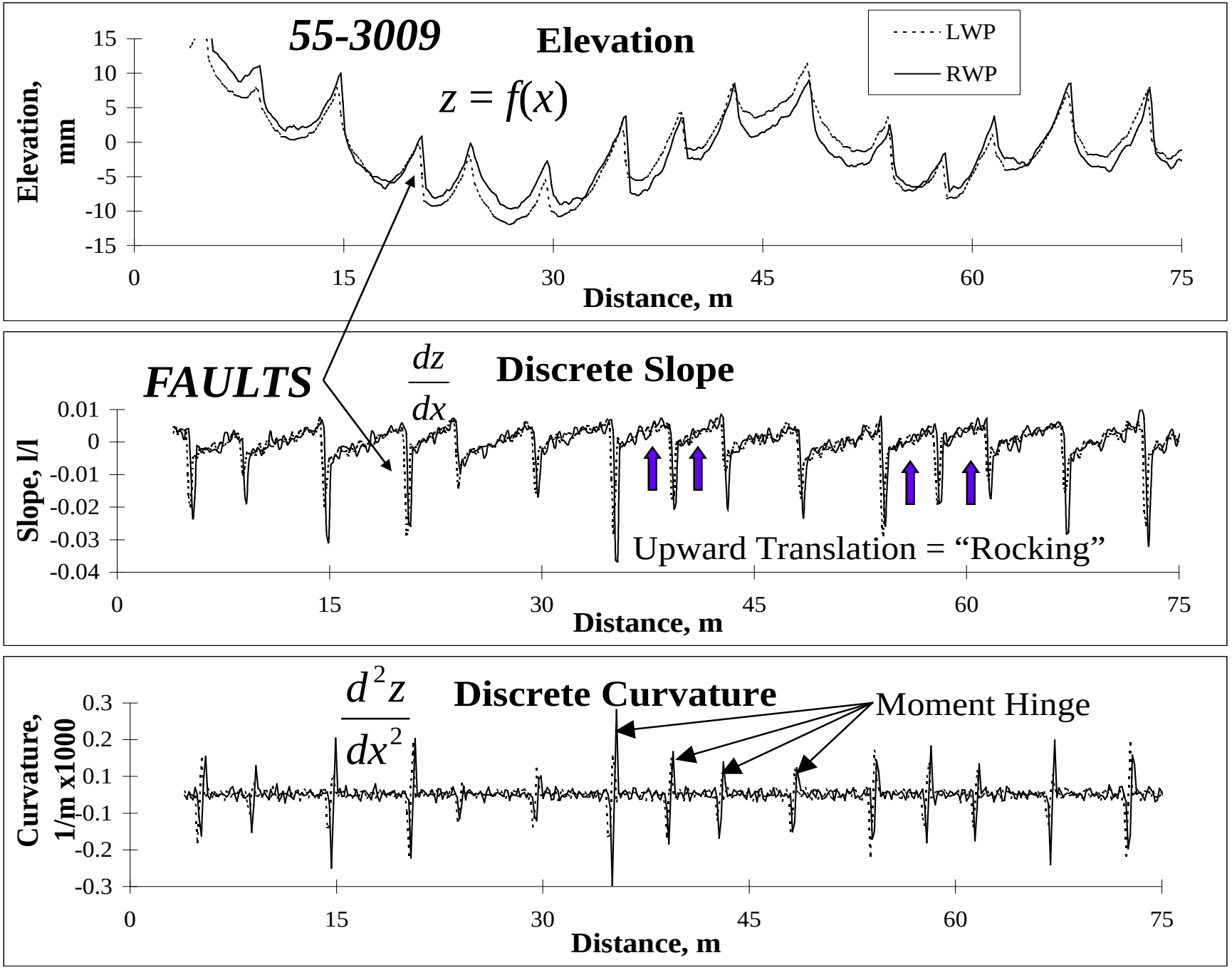


Traffic Direction

Site 553009 7/13/94 7:48:52 PM



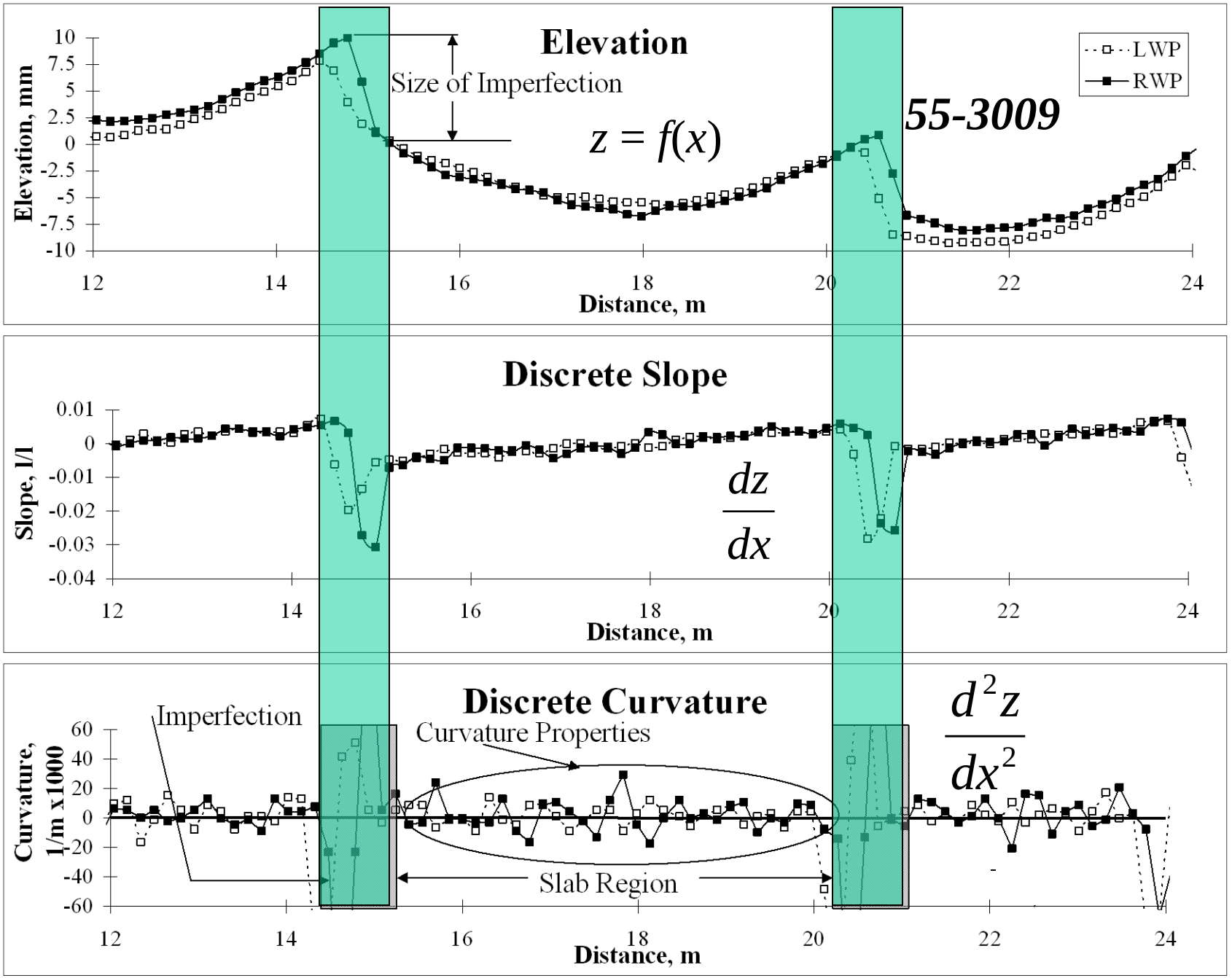
Traffic Direction


55-3009
Elevation
$z = f(x)$
LWP
RWP
Elevation, mm
15
10
5
0
-5
-10
-15
0
15
30
45
60
75
Distance, m
FAULTS
$\frac{dz}{dx}$
Discrete Slope
Slope, l/l
0.01
0
-0.01
-0.02
-0.03
-0.04
Upward Translation = “Rocking”
Distance, m
$\frac{d^2z}{dx^2}$
Discrete Curvature
Moment Hinge
Curvature, 1/m x1000
0.3
0.2
0.1
-0.1
-0.2
-0.3
Distance, m

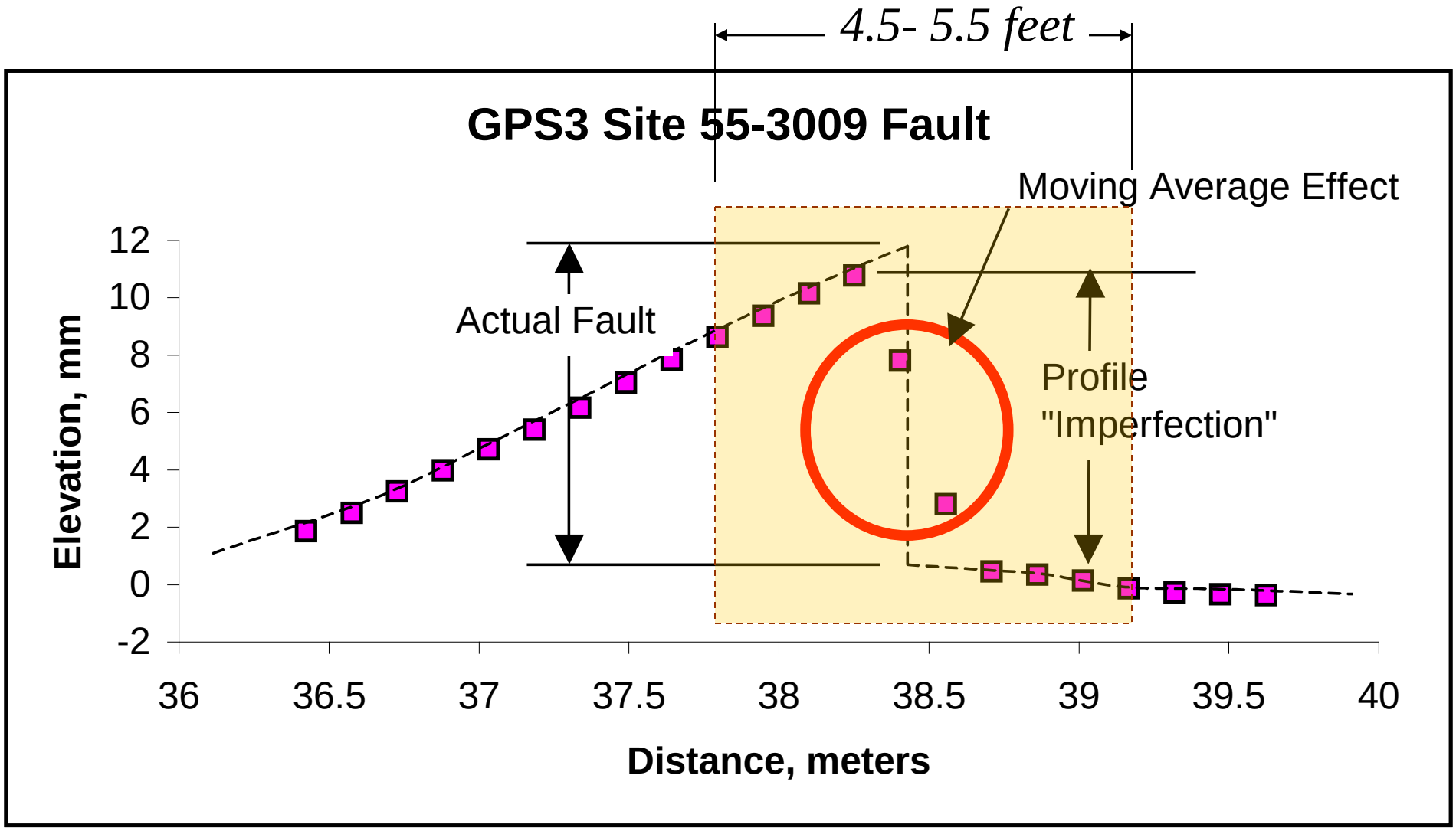
Beam Equation

$$M = EI\frac{d^2z}{dx^2}$$

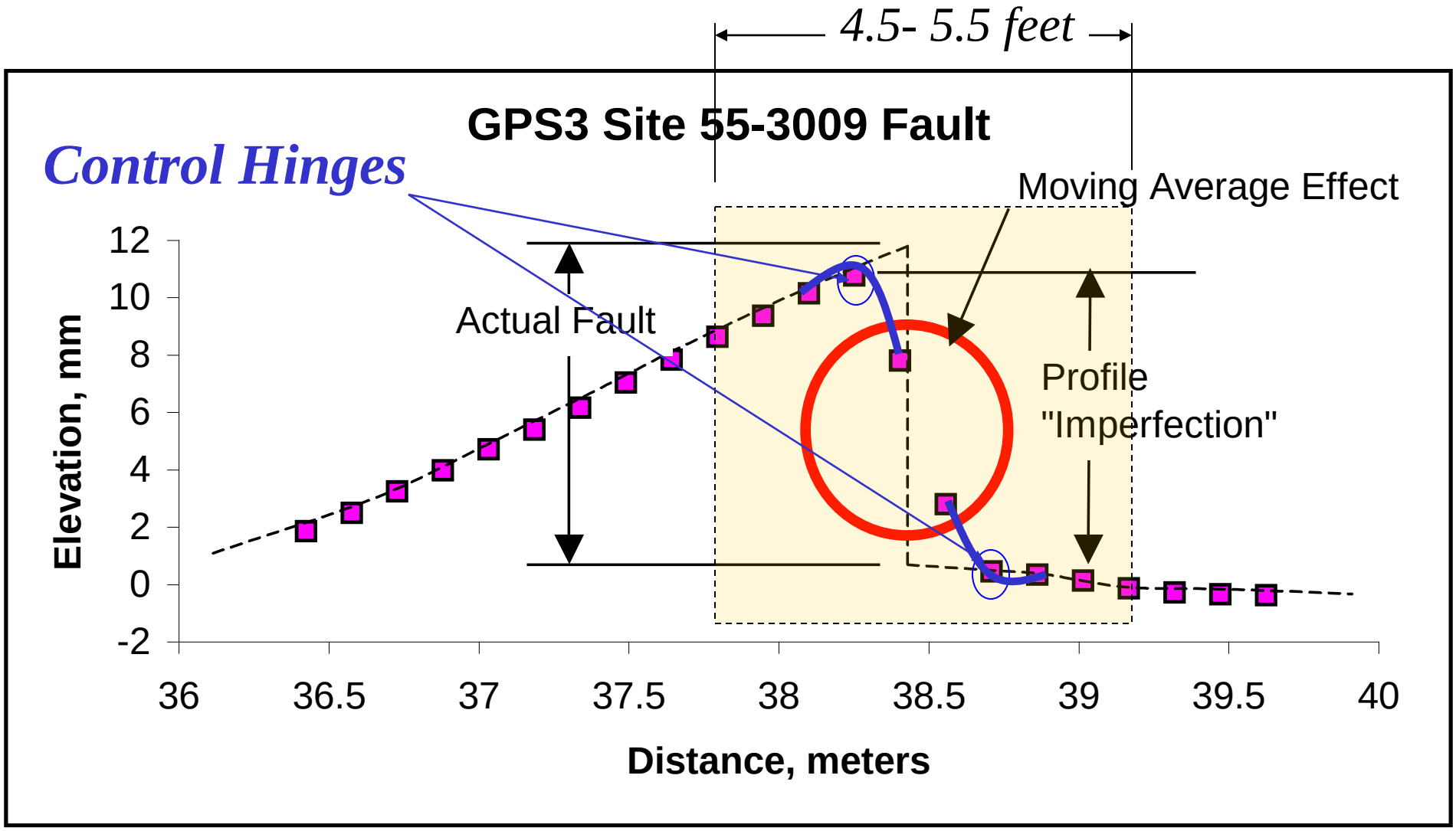
This Concept is Not valid at a Hinge

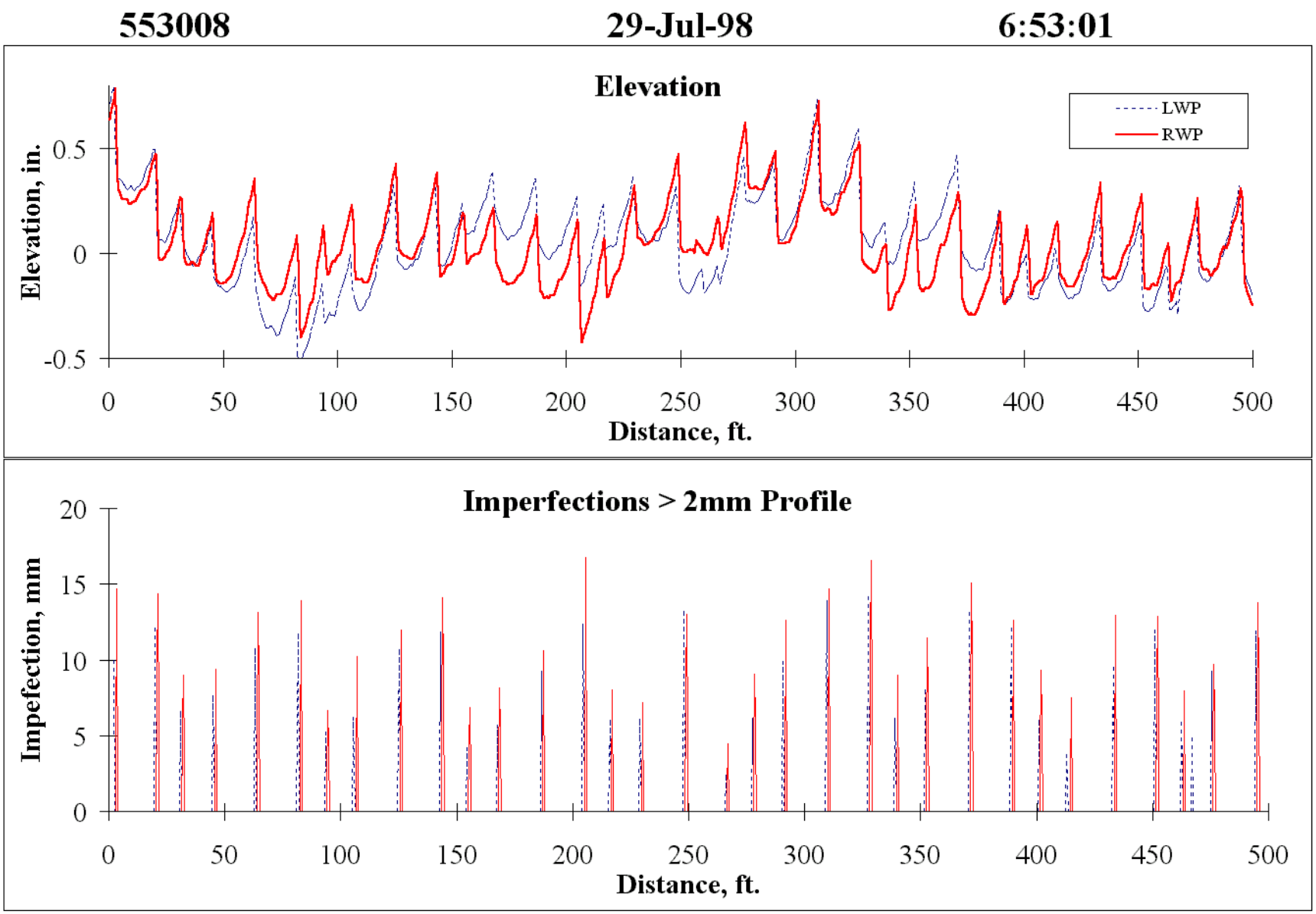

Elevation
Size of Imperfection
$z = f(x)$
55-3009
LWP
RWP
Elevation, mm
Distance, m
Discrete Slope
$\frac{dz}{dx}$
Slope, l/l
Distance, m
Discrete Curvature
$\frac{d^2z}{dx^2}$
Imperfection
Curvature Properties
Slab Region
Curvature, 1/m x1000
Distance, m

LTPP Profile Data at a Fault



LTPP Profile Data at a Fault





…for All GPS3 Sites, through year 2007

Site ID: 553008

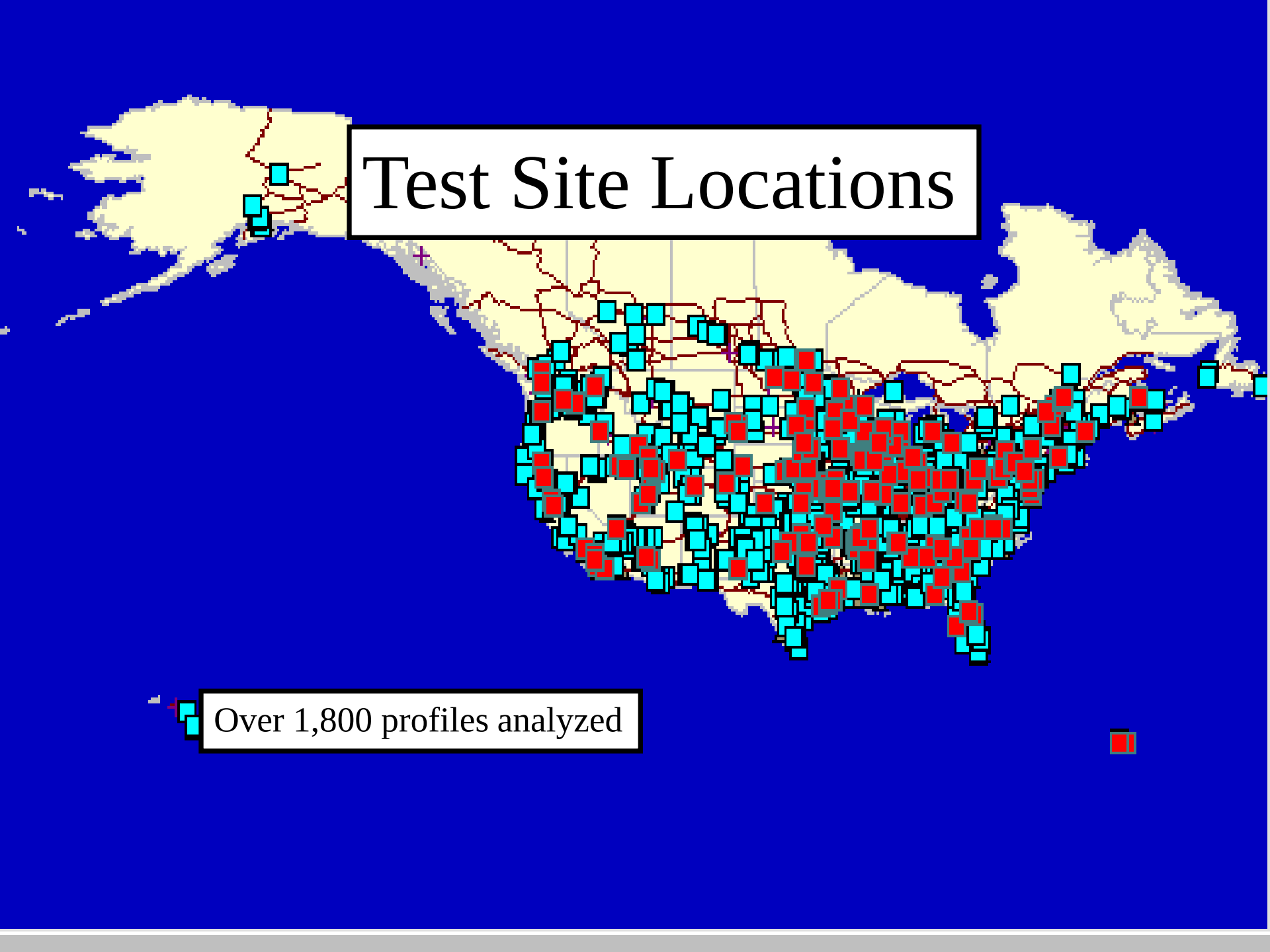
Profile Date: 7/29/98

ProfileTime: 6:53:01

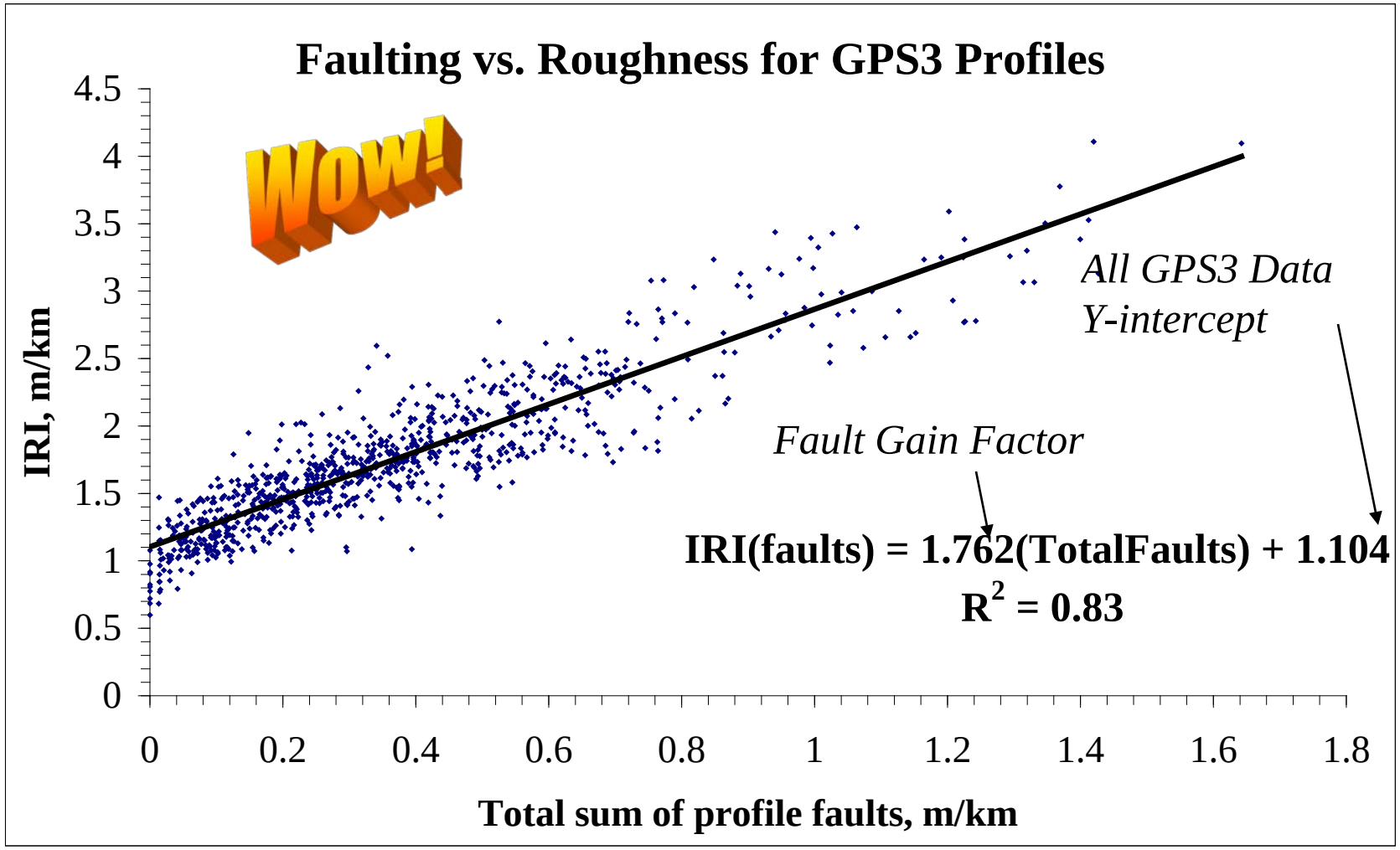
500-ft Summary Statistics	**LWP**	**RWP**
# Imperfections detected	34	33
Average Size, mm	8.8	11.1
Maximum Size, mm	14.2	16.7
Minimum Size, mm	2.4	4.4
Total Imperfections, mm	298.7	367.8
Total Imperfections, m/km	**1.96**	**2.41**
Calculated IRI, m/km	**4.42**	**5.43**

Calculated – 1.75(Total) ***1.0*** ***1.2 ➔ IRI (0)***

…for All GPS3 Sites, through year 2007

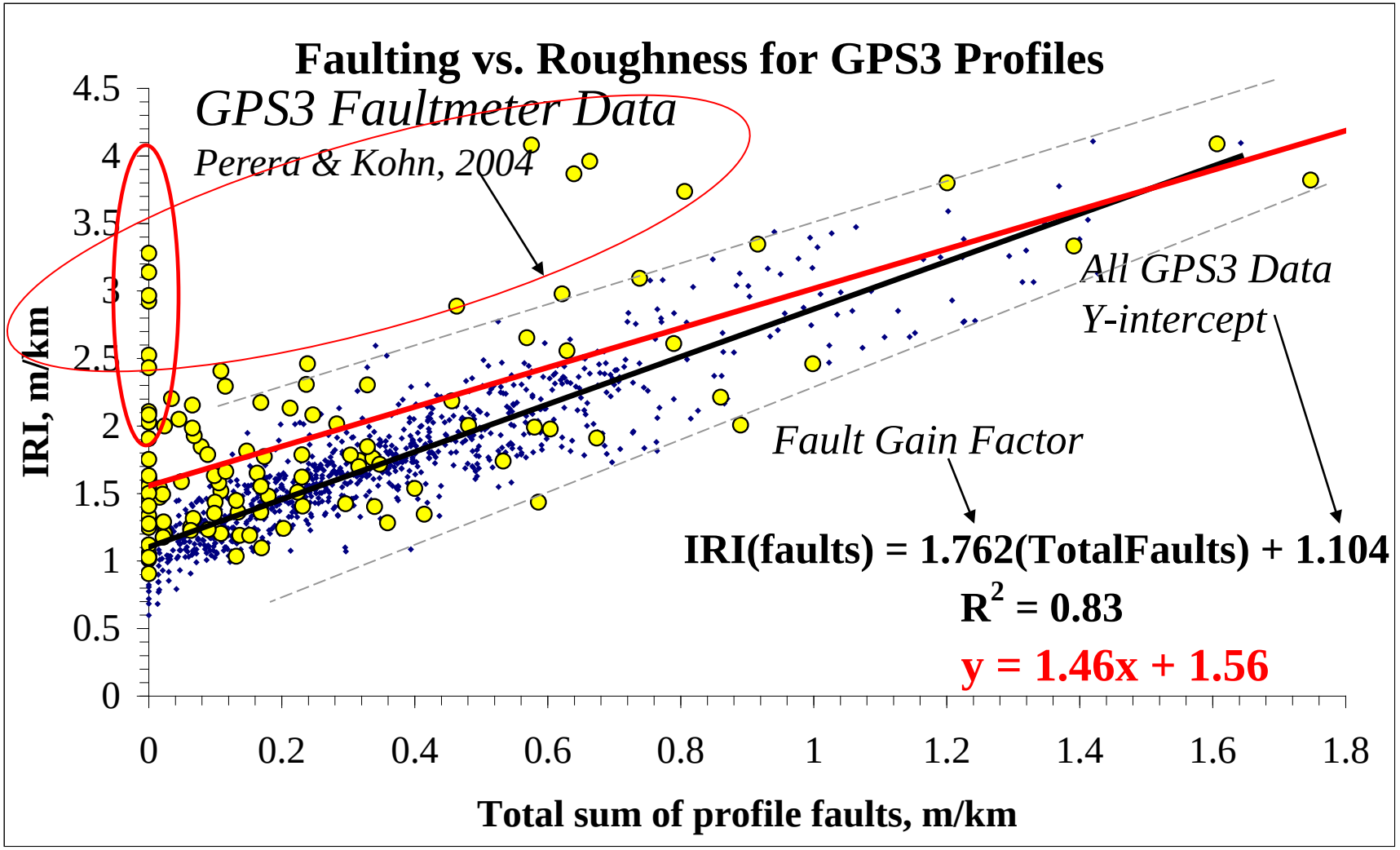

Test Site Locations
Over 1,800 profiles analyzed

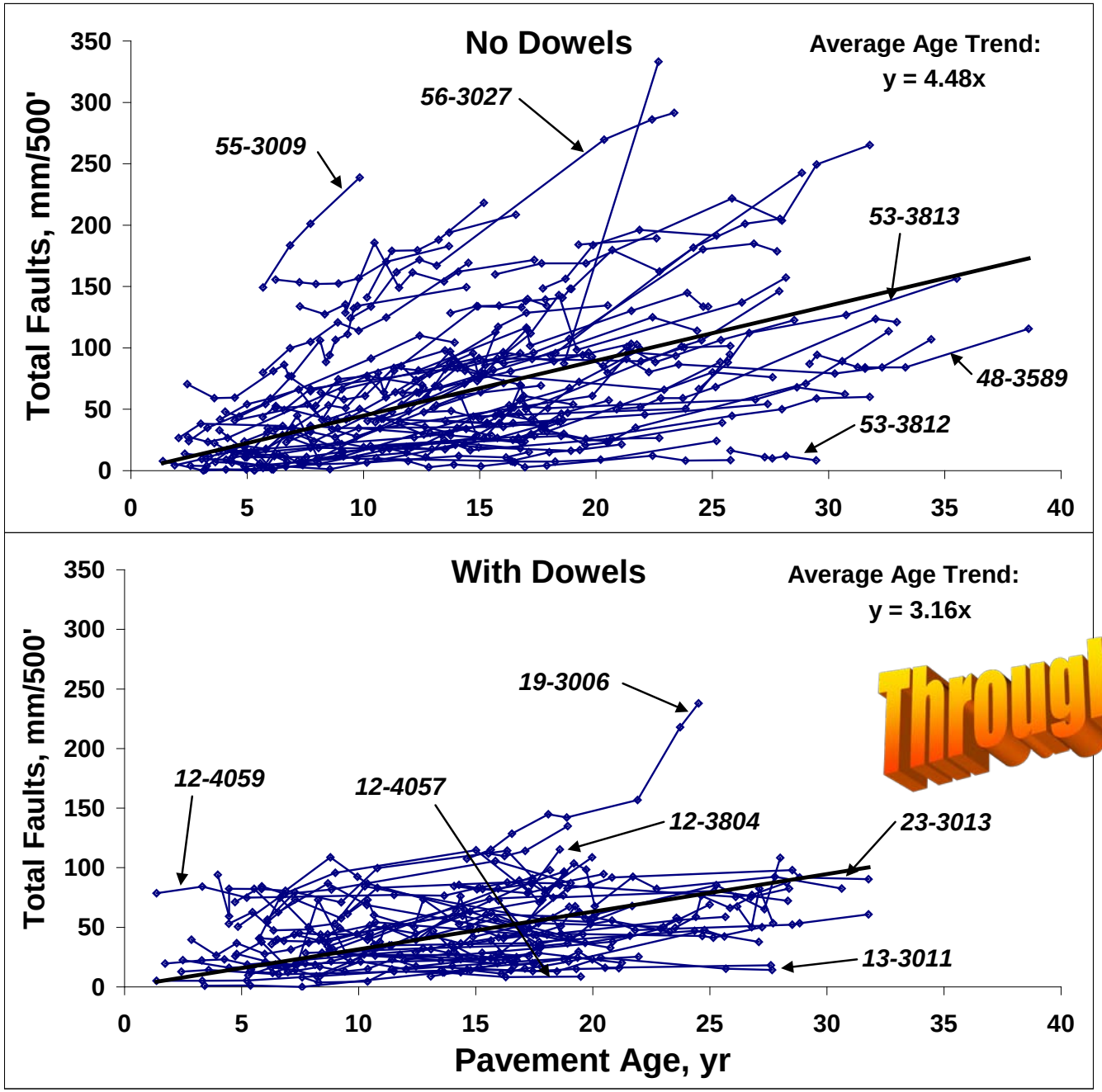
The Primary Cause of IRI- Faults

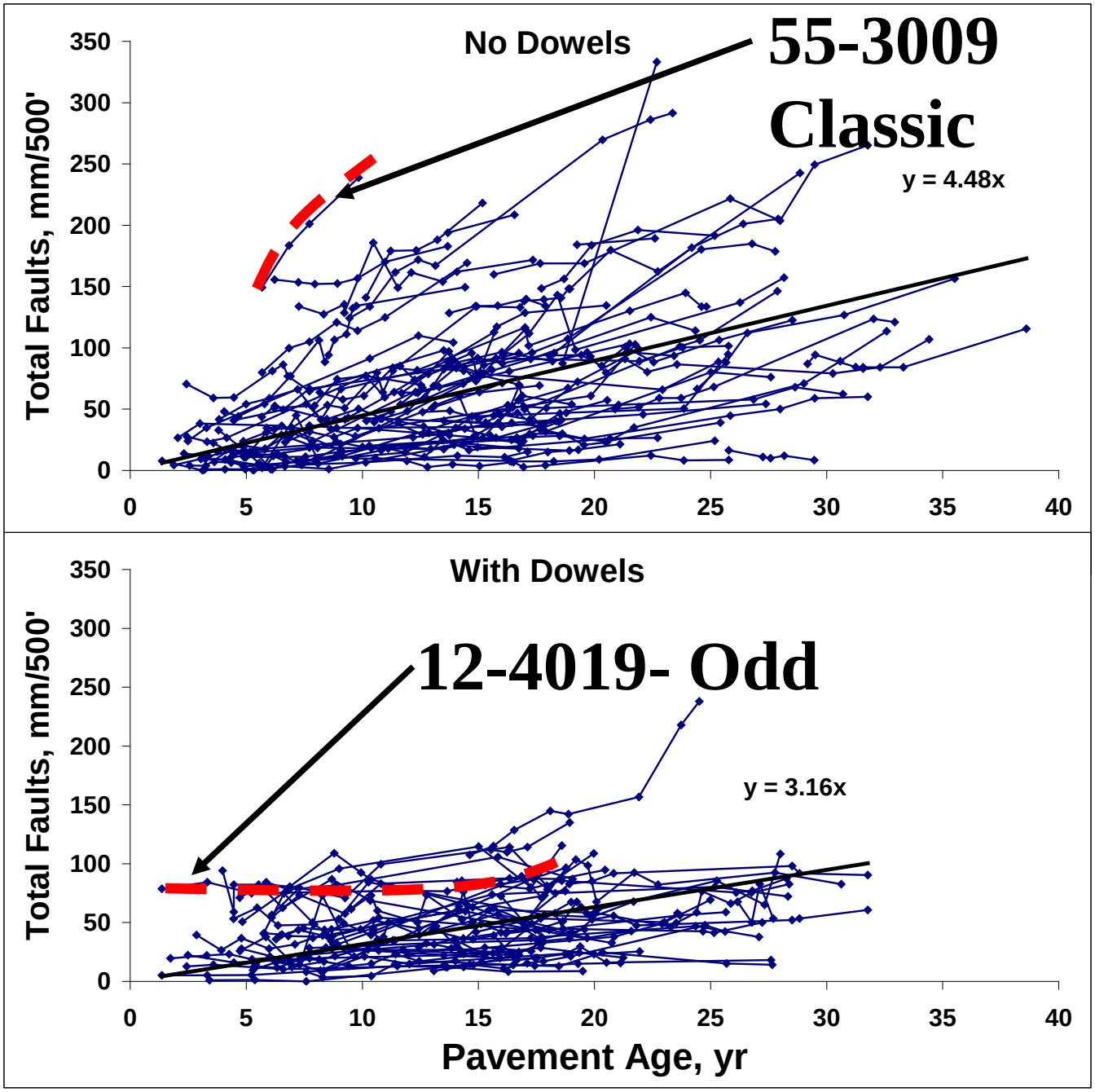


Byrum- 2000, Byrum & Perera- 2005

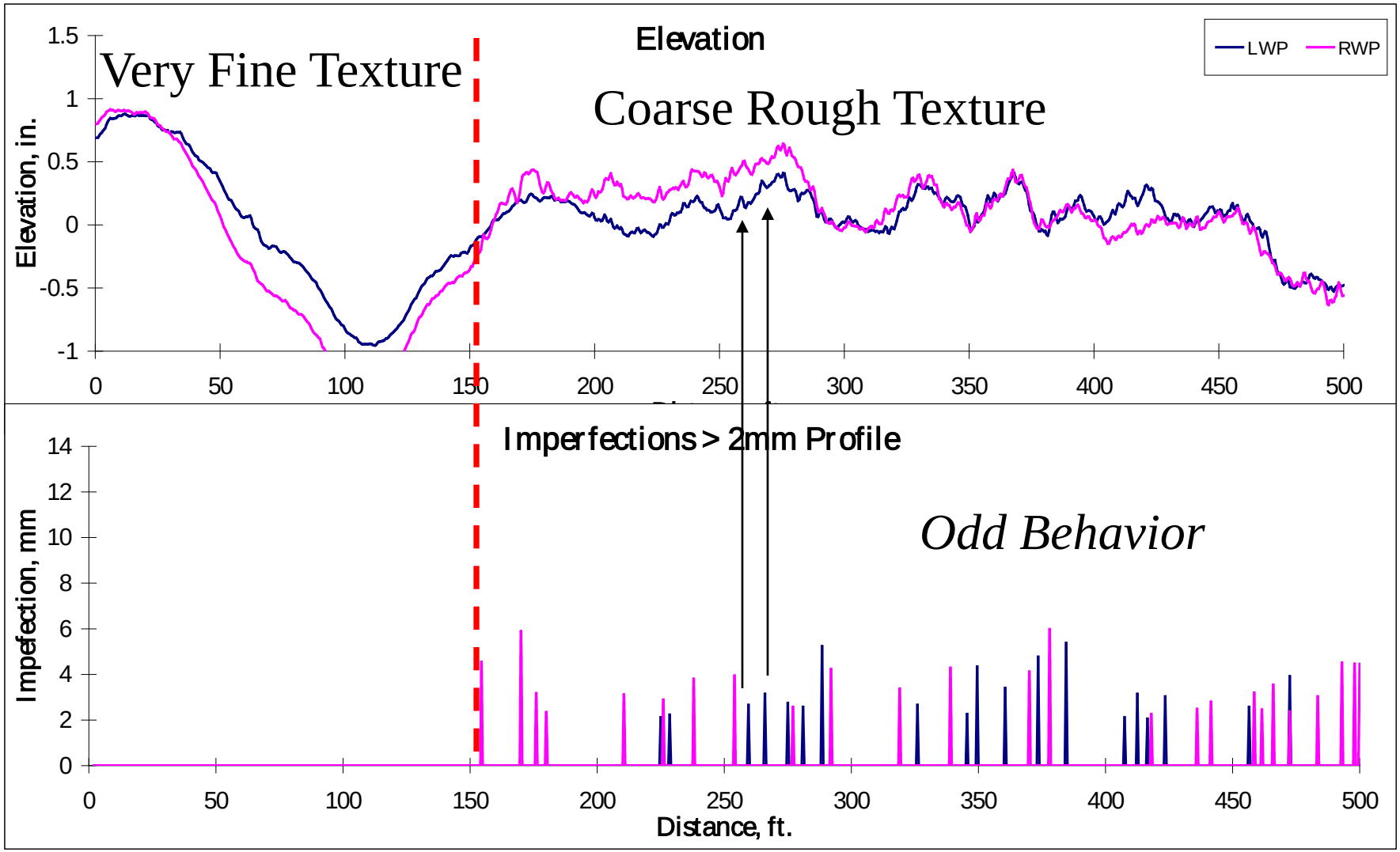
FAULTMETER vs. PROFILE Faults



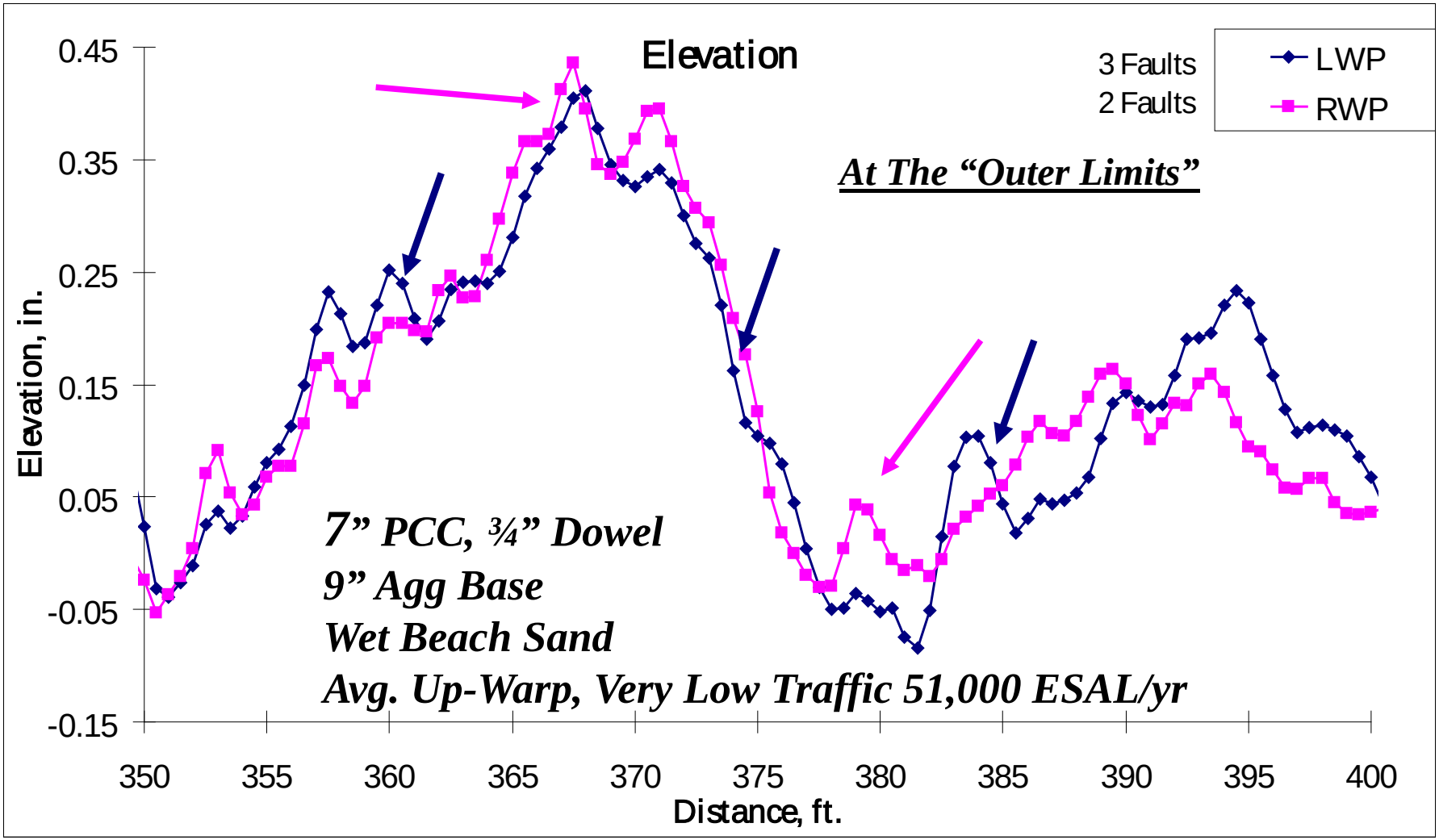

No Dowels
Average Age Trend:
y = 4.48x
Total Faults, mm/500'
56-3027
55-3009
53-3813
48-3589
53-3812
With Dowels
Average Age Trend:
y = 3.16x
Total Faults, mm/500'
19-3006
12-4059
12-4057
12-3804
23-3013
13-3011
Pavement Age, yr
Through 2007


No Dowels
55-3009
Classic
y = 4.48x
Total Faults, mm/500'
350
300
250
200
150
100
50
0
0
5
10
15
20
25
30
35
40
With Dowels
12-4019- Odd
y = 3.16x
Total Faults, mm/500'
Pavement Age, yr

124109 **25-Jun-92** **15:30:50**

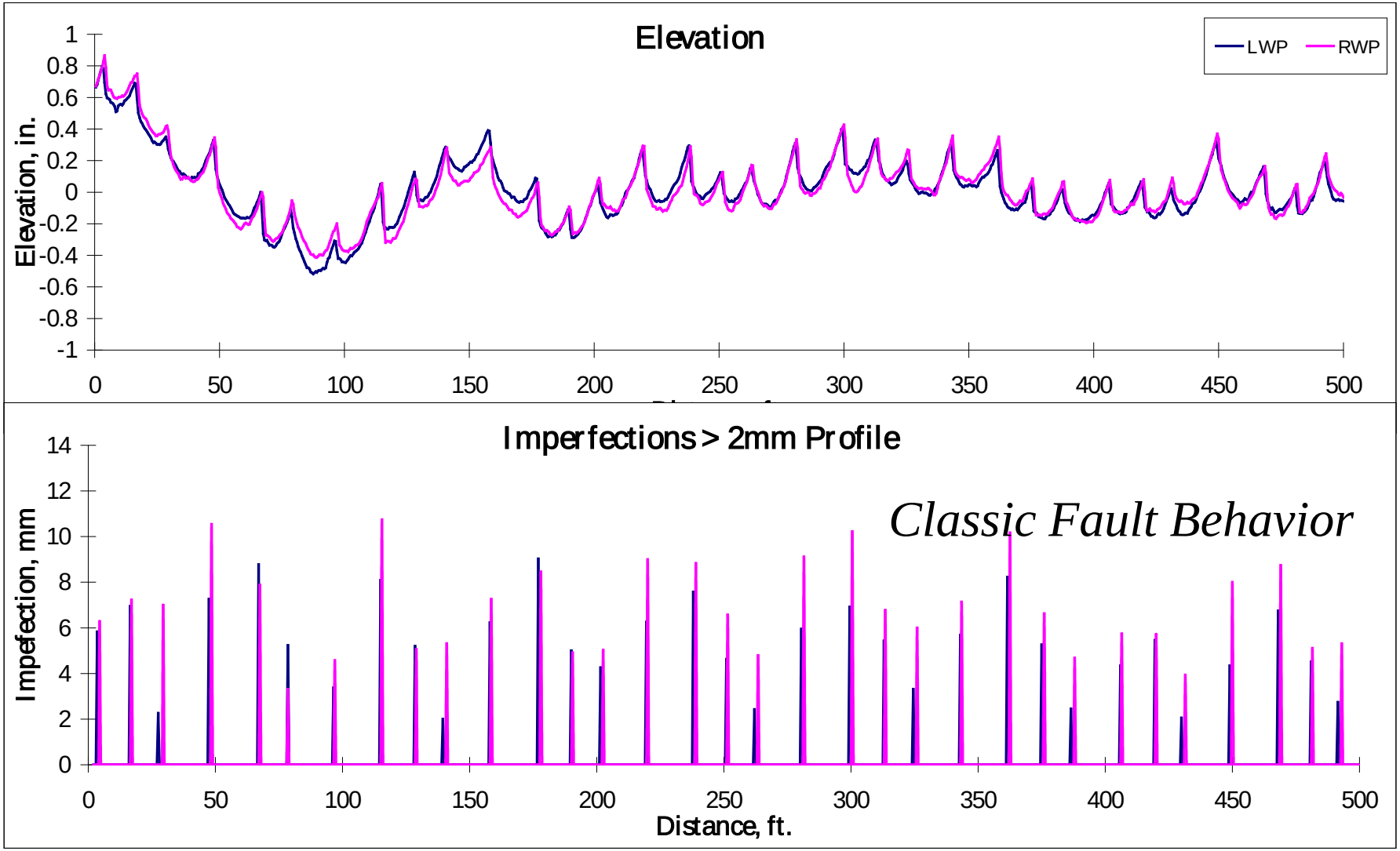


12-4019, Unusual Finishing, Very Coarse Texture, Shattered Slabs ????? Questionable

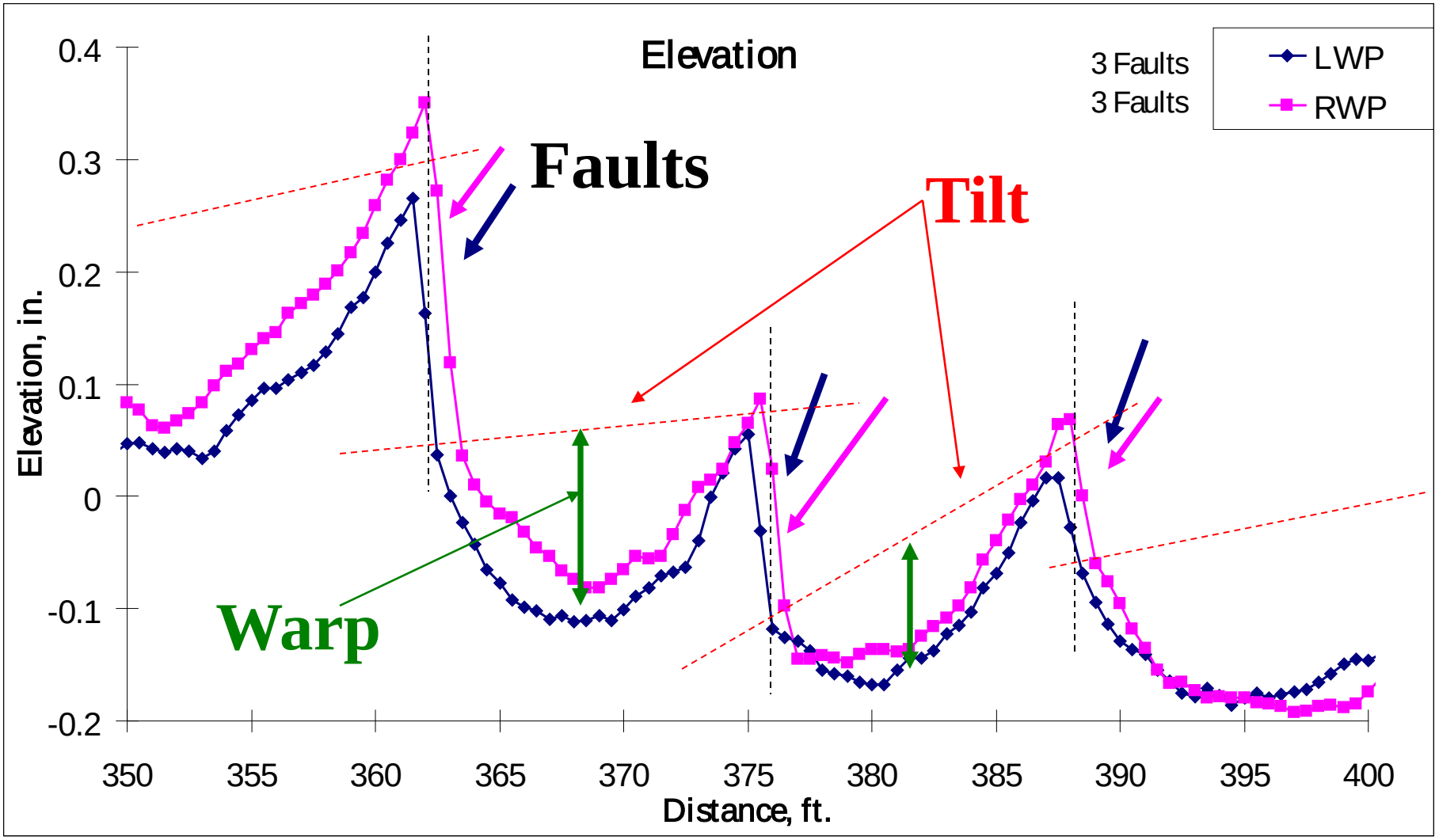


12-4019, Unusual Finishing, Very Coarse Texture, Shattered Slabs ????? Questionable

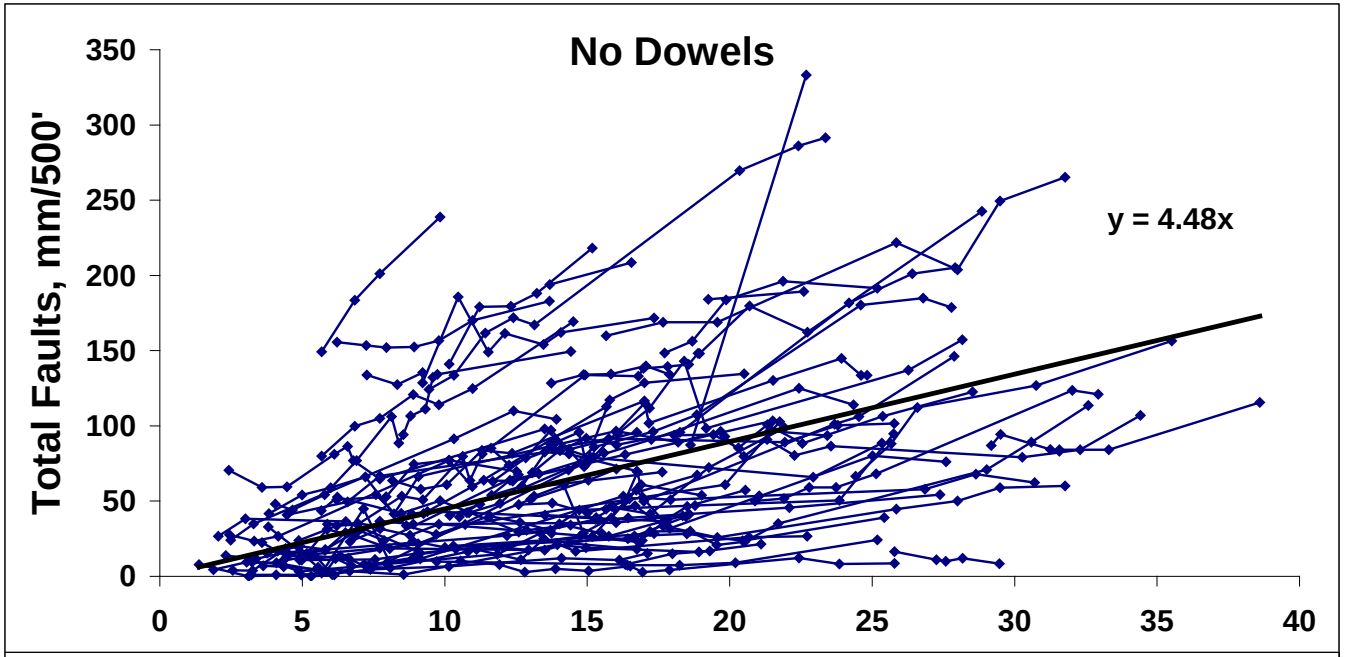
553009 **19-Jun-92** **15:51:44**

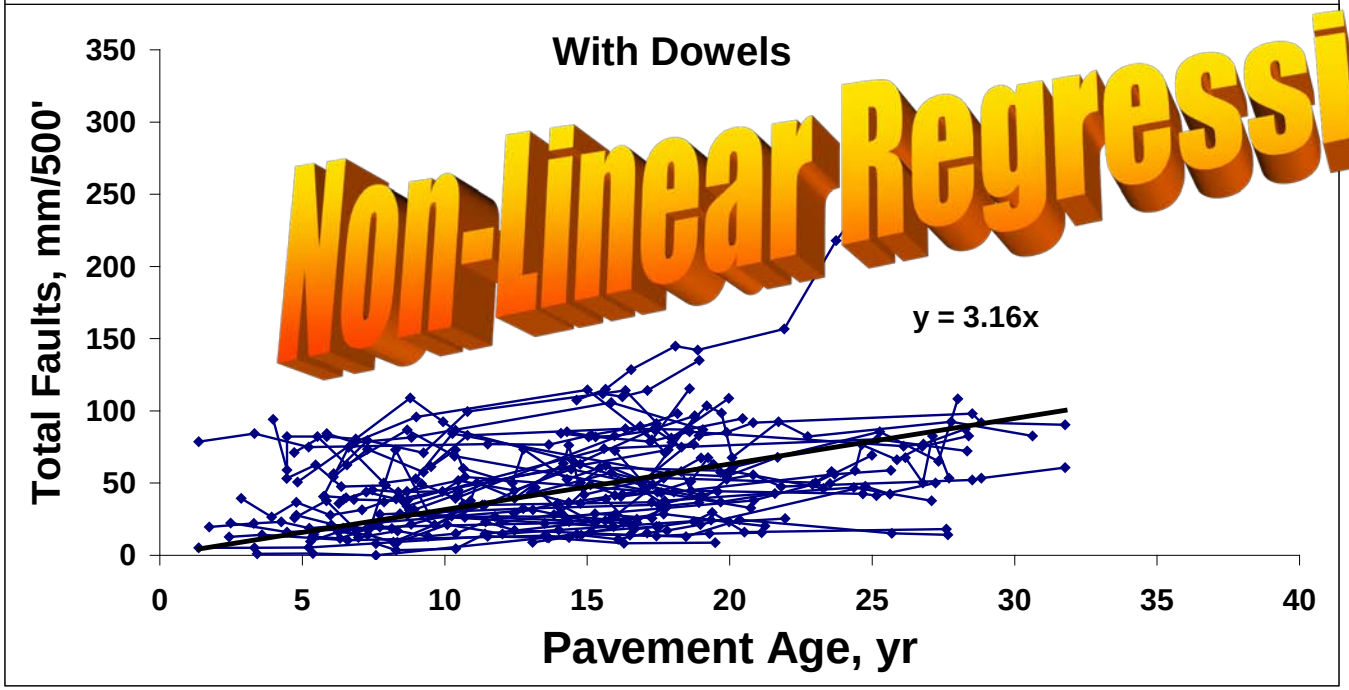


55-3009 Classic Real Faults with Fine Texture



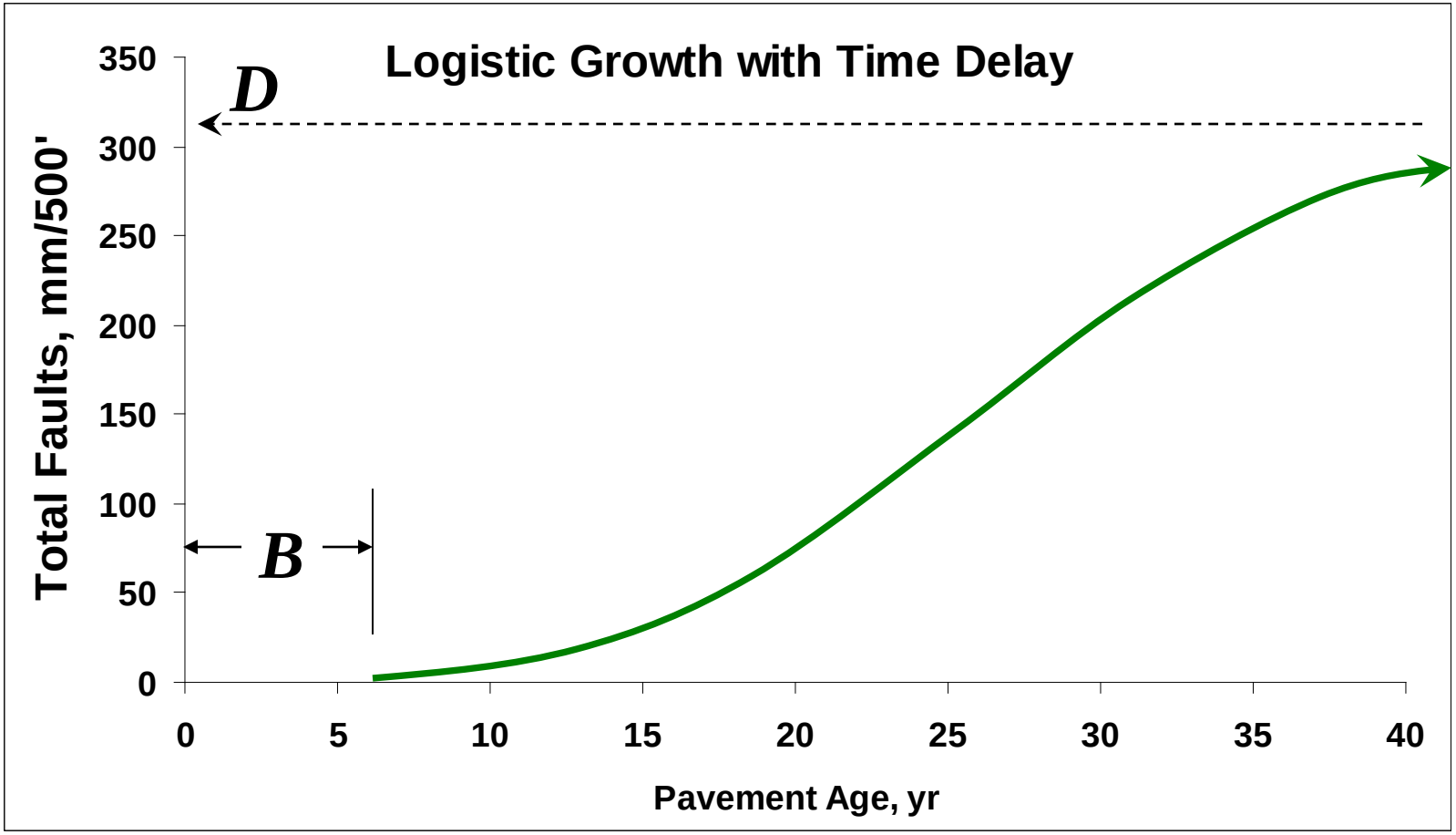
55-3009 Classic Real Faults with Fine Texture



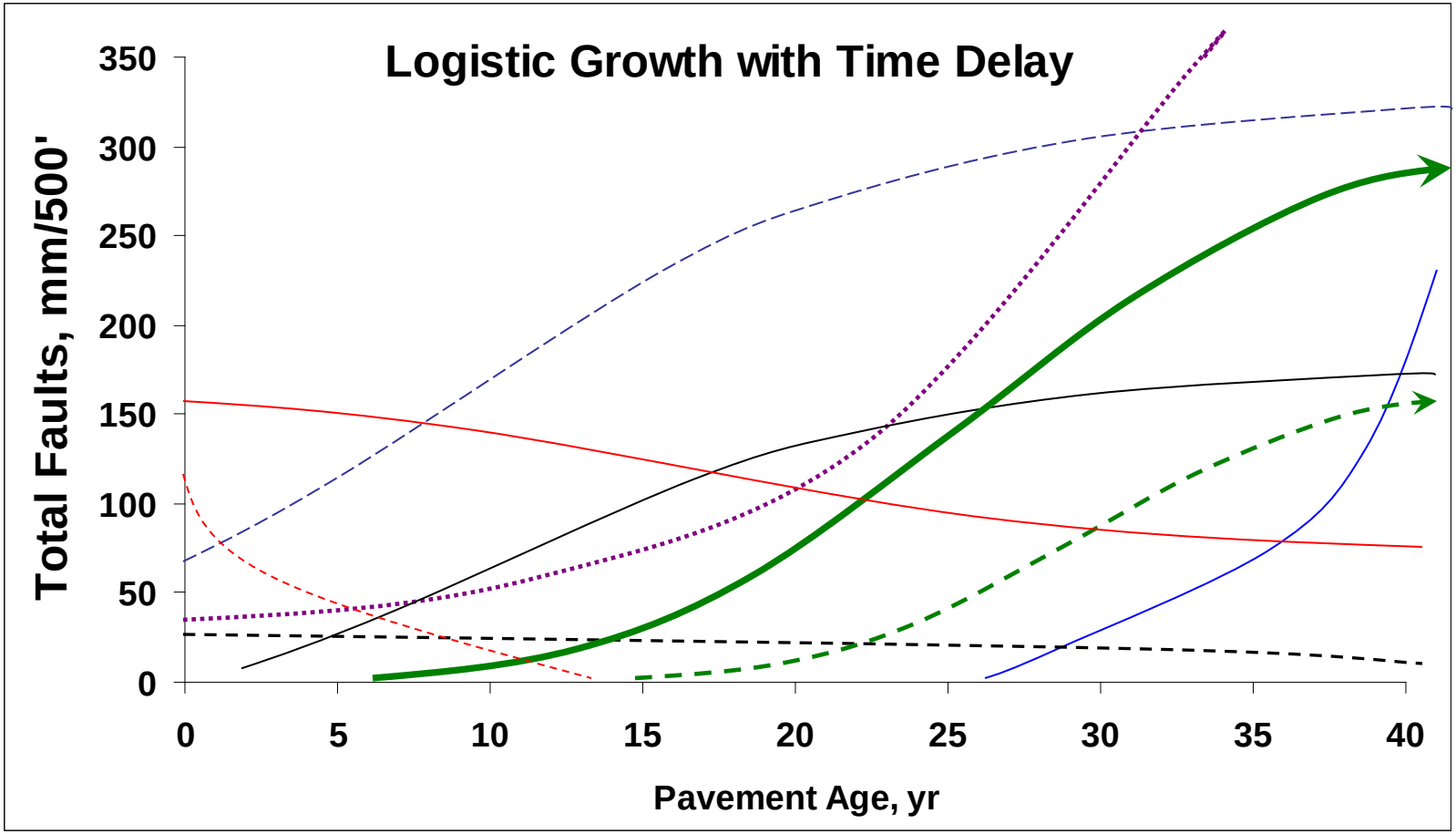


Non-Linear Regression

$$Faulting = \frac{D(A)e^{C(t-B)}}{[D - A + (A)e^{C(t-B)}]} - A$$



$$Faulting = \frac{D(A)e^{C(t-B)}}{[D - A + (A)e^{C(t-B)}]} - A$$



Set A, B, C, D as functions of……

CI = average slab curvature, in ft^{-1} x 1000
PCCThick = slab thickness in inches
P_0 = overburden pressure on the subgrade in psf
w% = subgrade soil moisture content in percent
P200 = subgrade soil percent passing the #200 sieve size
DaysWet = Number of days having precipitation per year
FZI = site freezing index in ºF-days per year
AnnPrecip = site annual precipitation in inches
Days32 = number of days per year below 32 F
Days90 = number of days per year above 90 F
JtSp = constructed joint spacing in feet
EMOD = slab concrete elastic modulus in psi
SplitT = slab concrete split tensile strength in psi

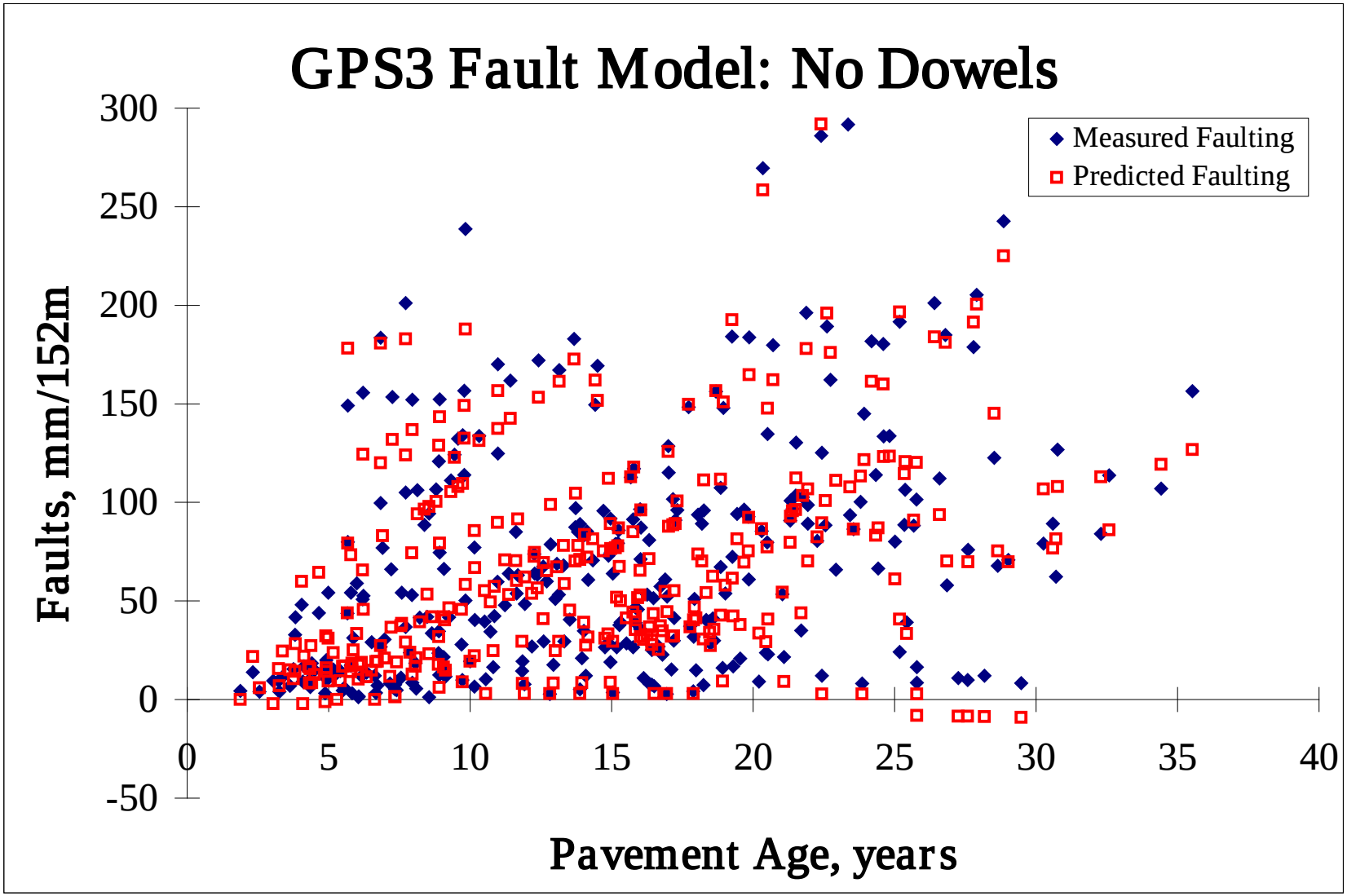
Exponential Growth Traffic Model is Embedded (GPS3 Traffic Models per Byrum and Kohn, 2003)

$$\boldsymbol{A} = A(1+CI)^{B} + C(PCCThick)^{D} + E(P_0/w\%)^{F}$$

$$\boldsymbol{B} = XB + G(1+CI)^{H} + I(SplitT/100)^{J} + K(P_0/w\%)^{L} + M(DaysWet)^{N} + O(PCCThick)^{P} + Q[(FZI+10)/P_0]^{R}$$

$$\boldsymbol{C} = 0.00001\{XC + S(1+CI)^{T} + U(KESALRate)^{V} + W(AnnPrecip)^{X} + Y(PCCThick)^{Z} + AA(Days32 + 1)^{BB} + CC(Days90 + 1)^{DD} + EE[(EMOD/1000000)/(SplitT/100)]^{FF} + GG(w\%)^{HH} + II(JtSp)^{JJ} + KK(P200)^{LL}\}$$

$$\boldsymbol{D} = XD + MM(1+CI)^{NN} + OO[P200(w\%)/P_0]^{PP} + QQ(JtSp)^{RR} + SS[(Days32)(DaysWet)]^{TT} + UU(CumTrf)^{VV}$$

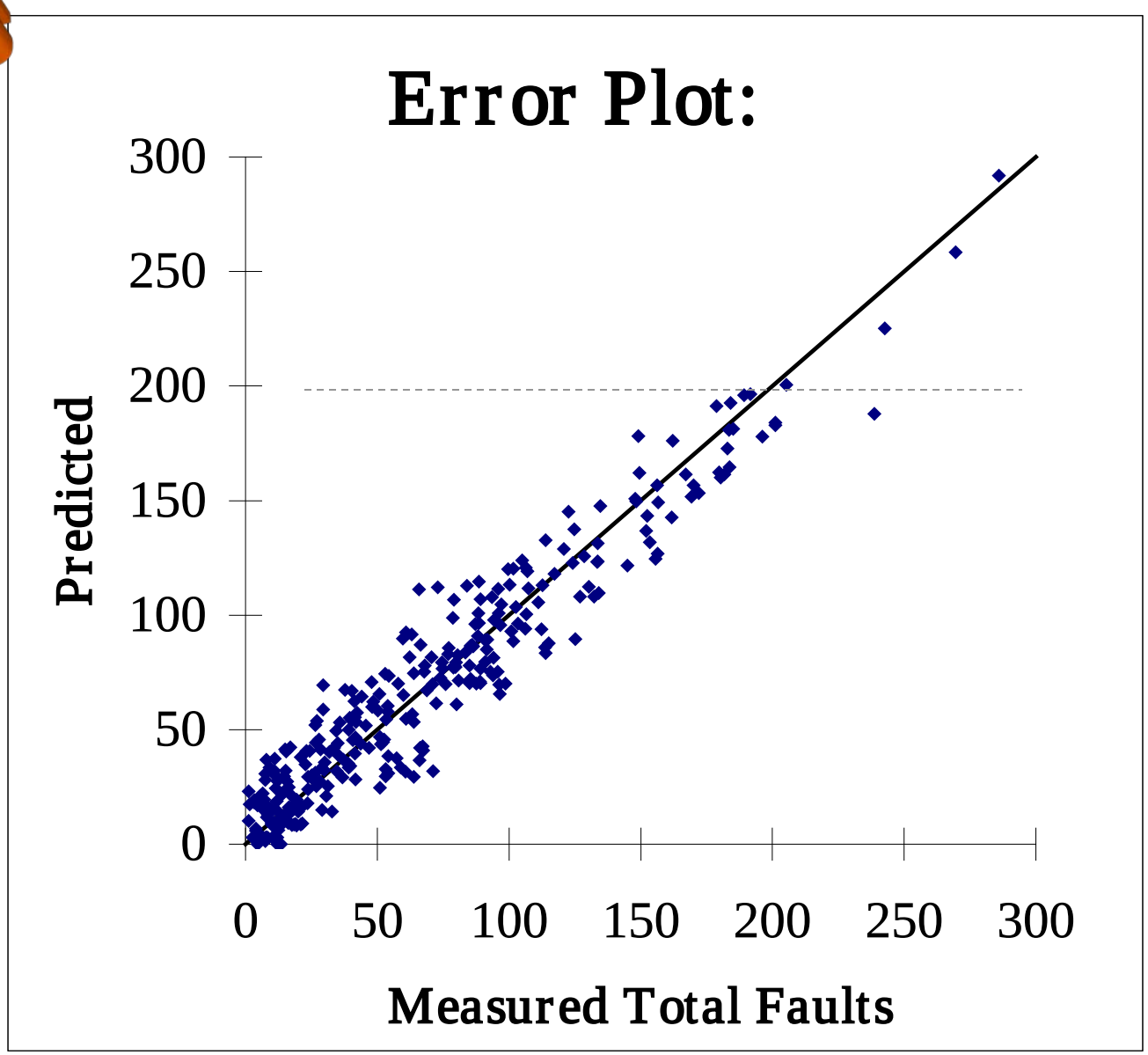

GPS3 Fault Model: No Dowels
Measured Faulting
Predicted Faulting
Faults, mm/152m
300
250
200
150
100
50
0
-50
0
5
10
15
20
25
30
35
40
Pavement Age, years

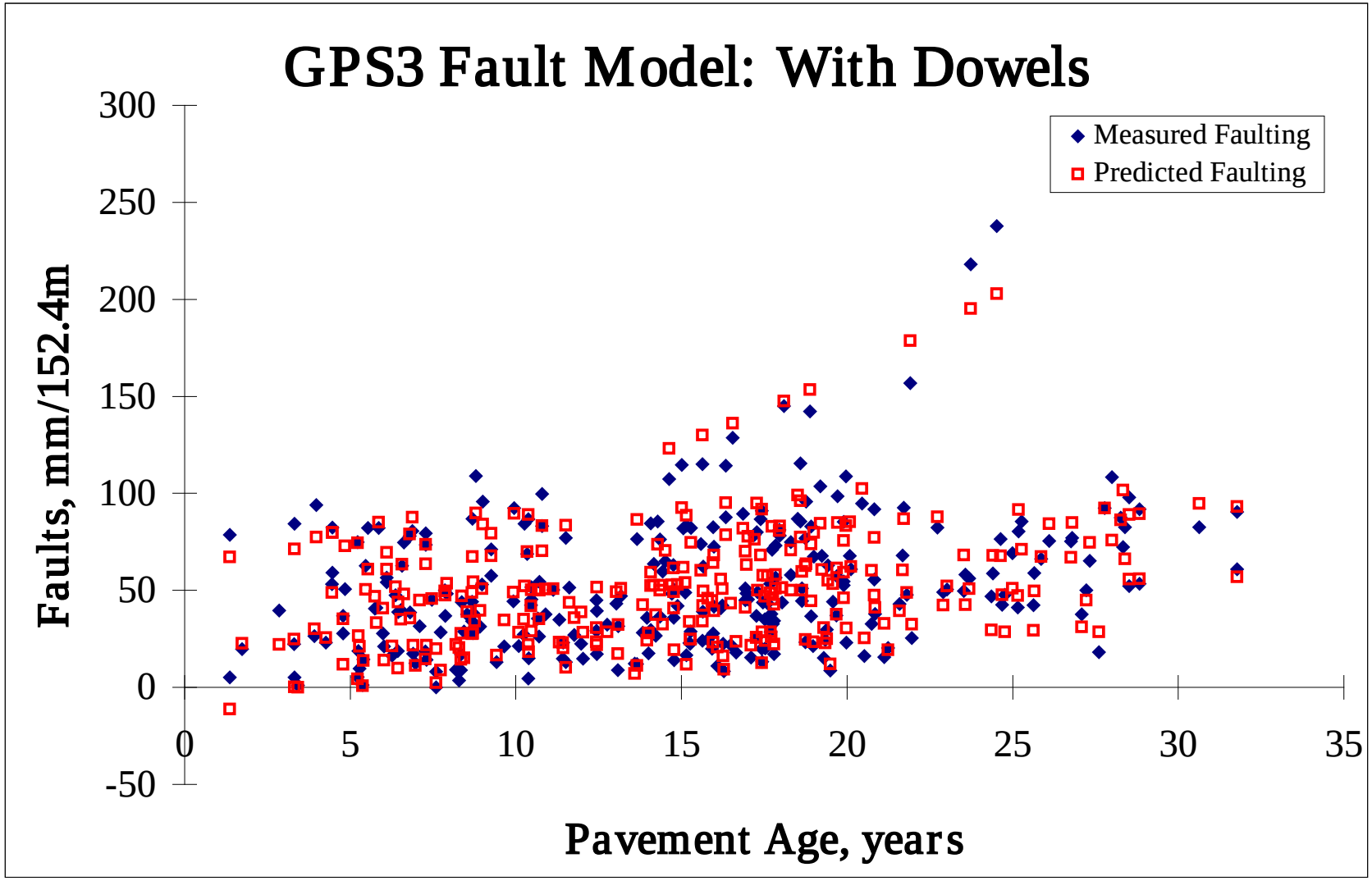
No Dowels

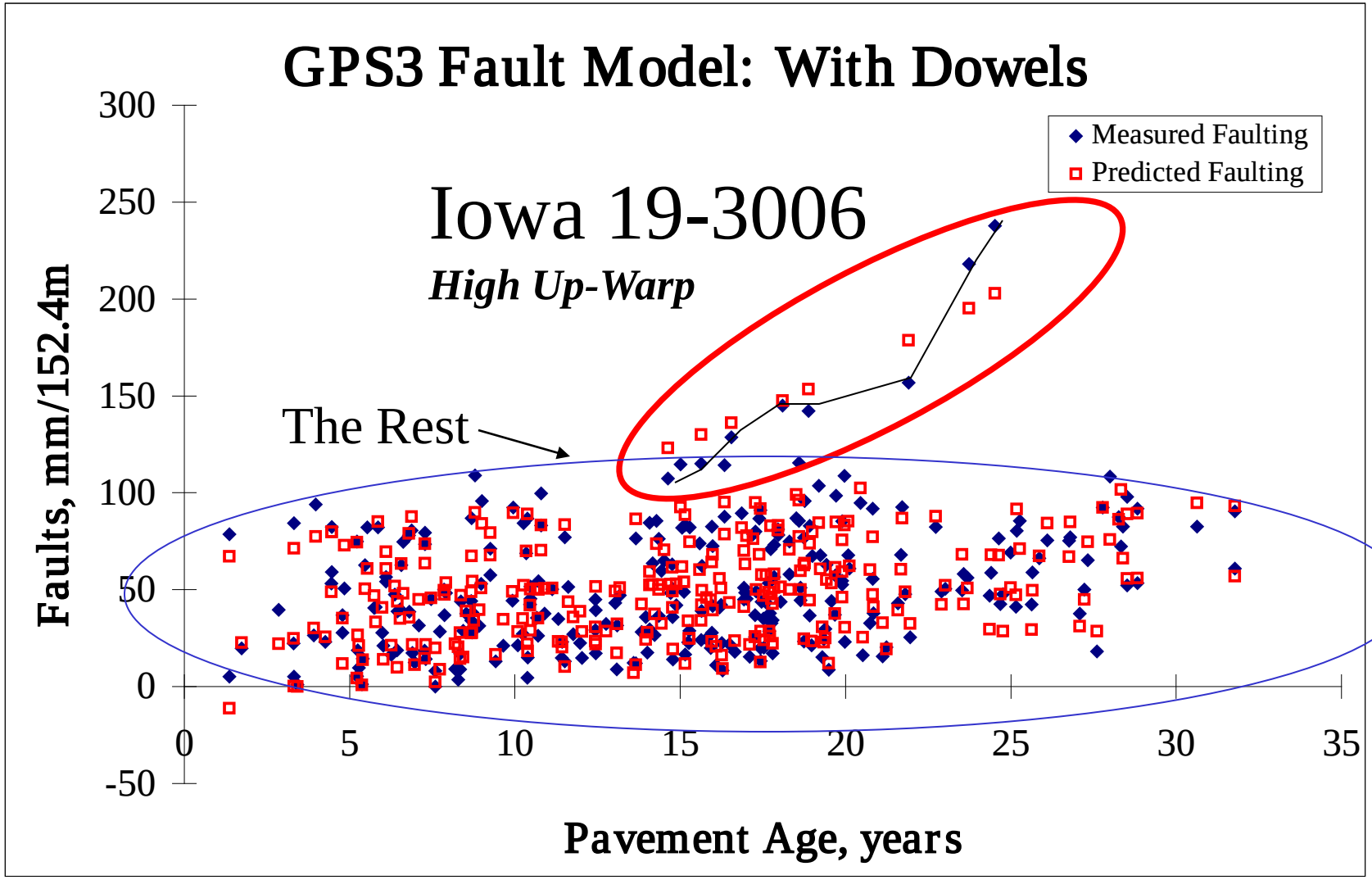
$r^2 = 0.93$

Std Error = 15.7

≈ 7% @ y=200




GPS3 Fault Model: With Dowels
Measured Faulting
Predicted Faulting
Faults, mm/152.4m
300
250
200
150
100
50
0
-50
0
5
10
15
20
25
30
35
Pavement Age, years

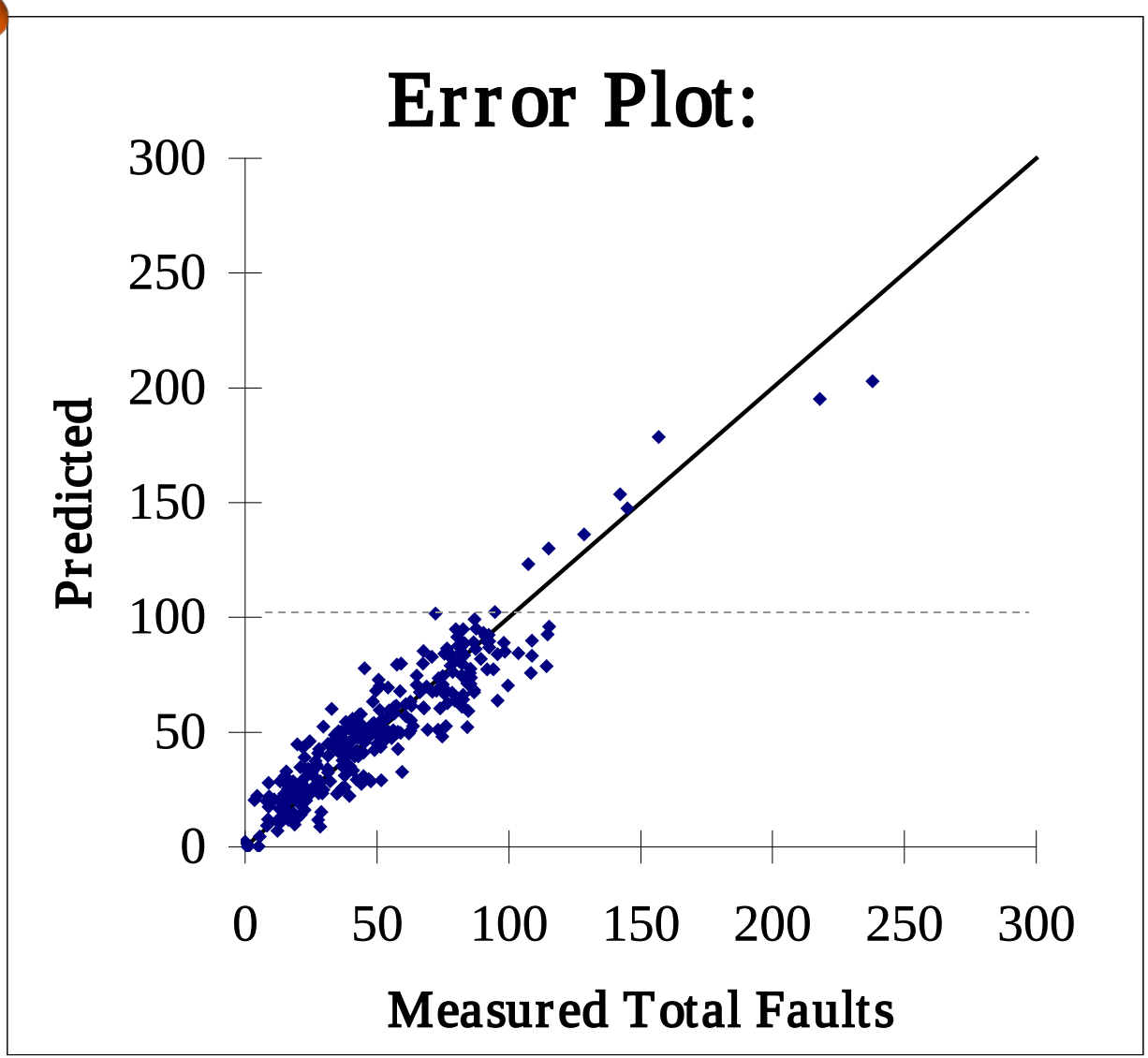

GPS3 Fault Model: With Dowels
Measured Faulting
Predicted Faulting
Iowa 19-3006
High Up-Warp
The Rest
Faults, mm/152.4m
300
250
200
150
100
50
0
-50
0
5
10
15
20
25
30
35
Pavement Age, years

With Dowels

$r^2 = 0.86$

Std Error = 12.6

≈ 14% @ y=100



The Design Tool

SPREADSHEET

Same Model Form
Different Coefficients

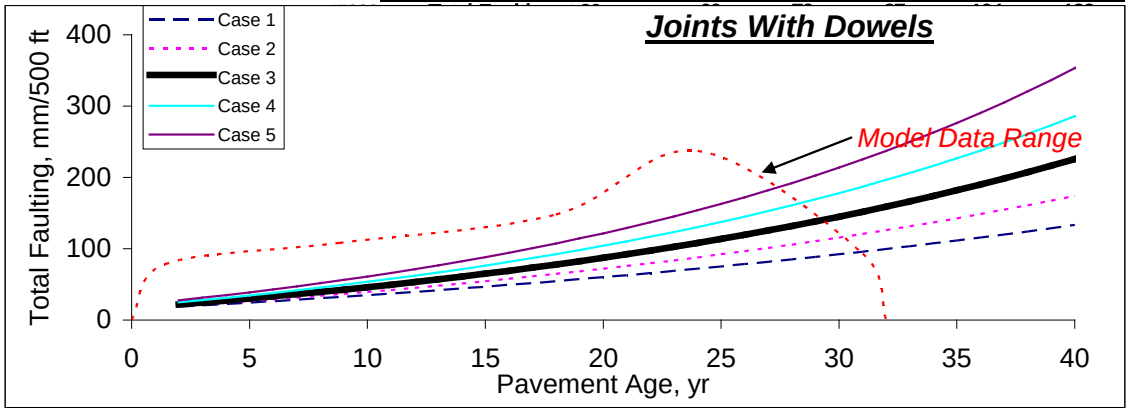
Traffic Model

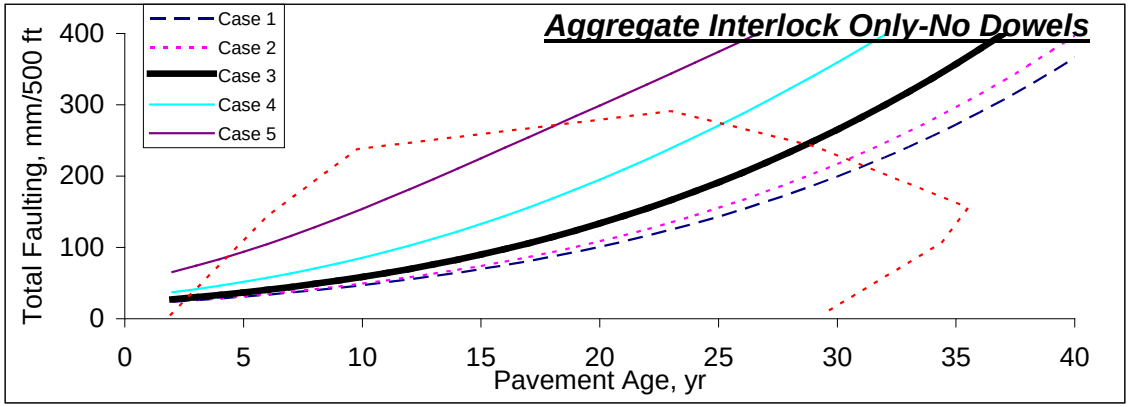
Data Ranges

Input Table

Trend Graphs

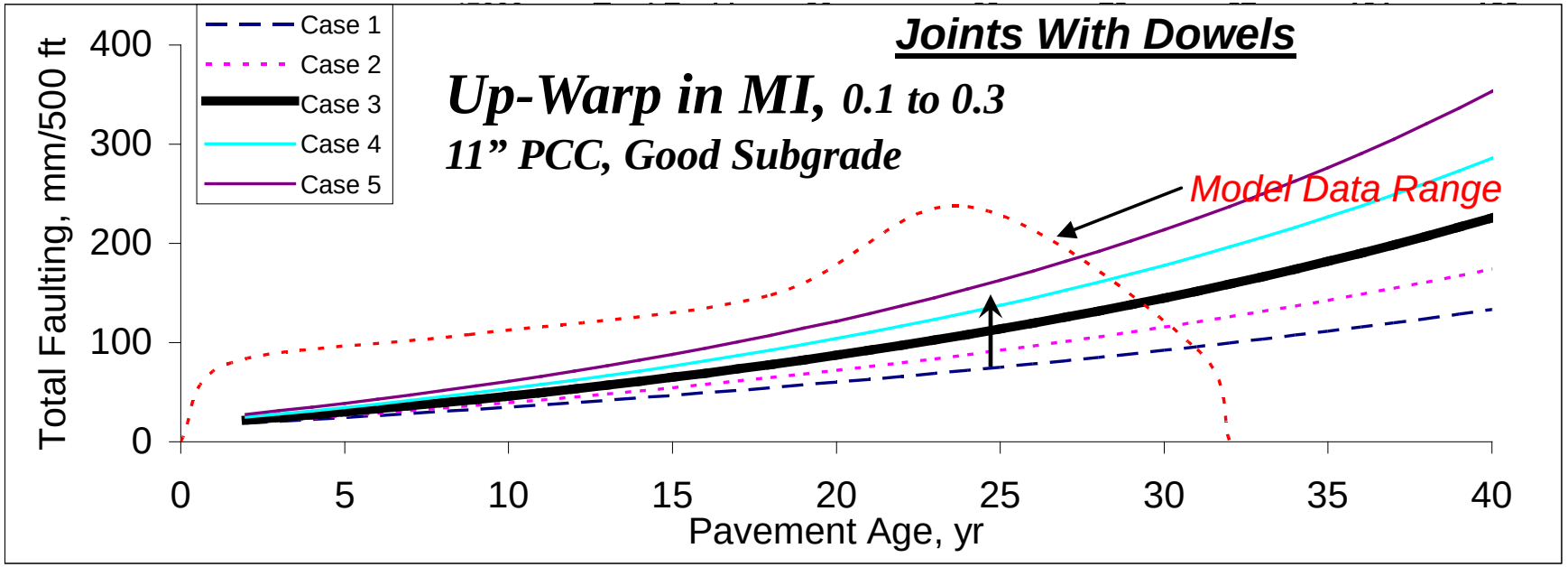
Agg Only Range	Dowels Range	INPUT DATA	Case 1	Case 2	Case 3	Case 4	Case 5
-0.1 to 0.43	-0.09 to +0.32	*Slab Curvature, ft^{-1} x 1000*	0.1	0.15	0.2	0.25	0.3
8 to14.3	6.4 to 13.3	*PCC thickness, in.*	11	11	11	11	11
2 to 6.6 mill.	3.35 to 5.68	*PCC E-modulus, psi*	4700000	4700000	4700000	4700000	4700000
460 to1000	466 to 738	*PCC Split Tensile, psi*	600	600	600	600	600
11 to 20	14 to 30	*Joint Spacing, ft*	20	20	20	20	20
100 to 680	103 to 376	*Subgrade Overburden, psf*	220	220	220	220	220
2.5 to 34	4.5 to 27.5	*Subgrade w%*	12	12	12	12	12
2 to 92	1 to 97	*Subgrade P200%*	25	25	25	25	25
33 to 181	40 to 170	*Days with precip/yr*	151	151	151	151	151
0 to 3396	0 to 2280	*Freeze Index, degF-days/yr*	1211	1211	1211	1211	1211
6 to 58	8 to 57	*Ann. Precipitation, in*	38	38	38	38	38
1 to 203	2 to 187	*Days < 32 degF/yr*	164	164	164	164	164
0 to 106	3 to 176	*Days > 90 degF/yr*	5	5	5	5	5
18 to 1470	18 to 820	*Initial KESAL/yr*	300	300	300	300	300
-0.05 to 0.2	-0.05 to 0.17	*Traffic Growth Rate, %/yr*	0.05	0.05	0.05	0.05	0.05

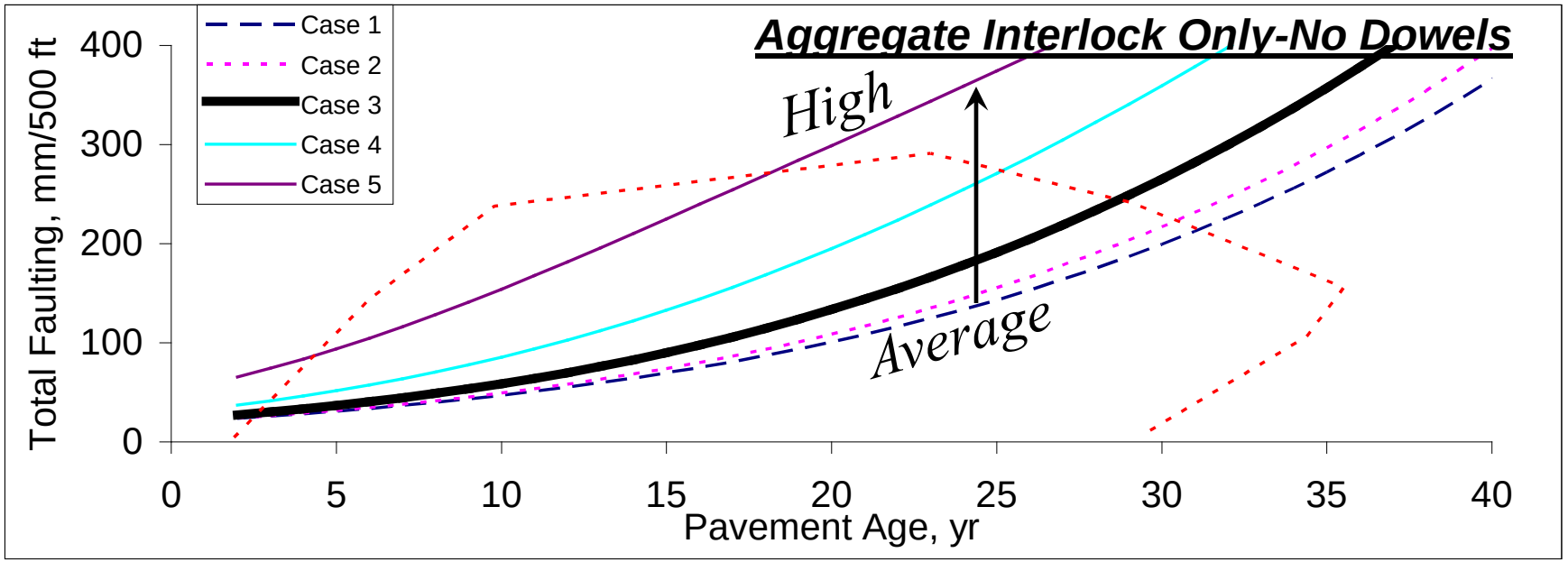


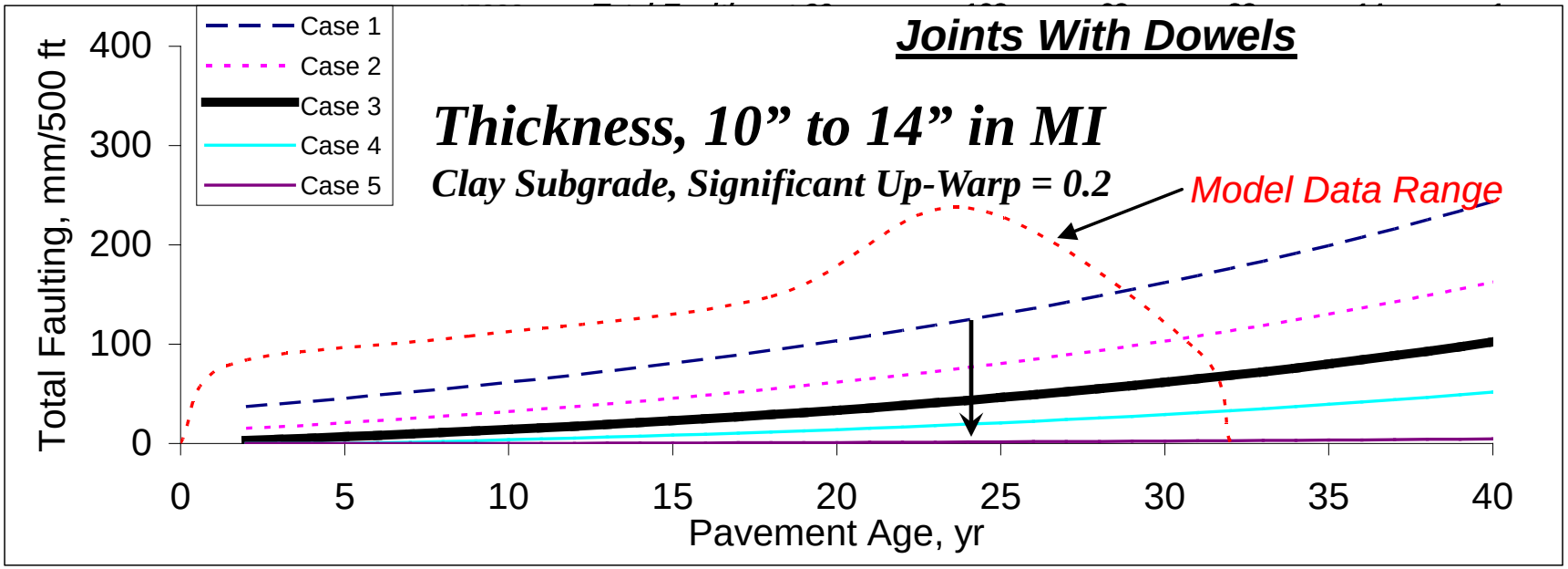


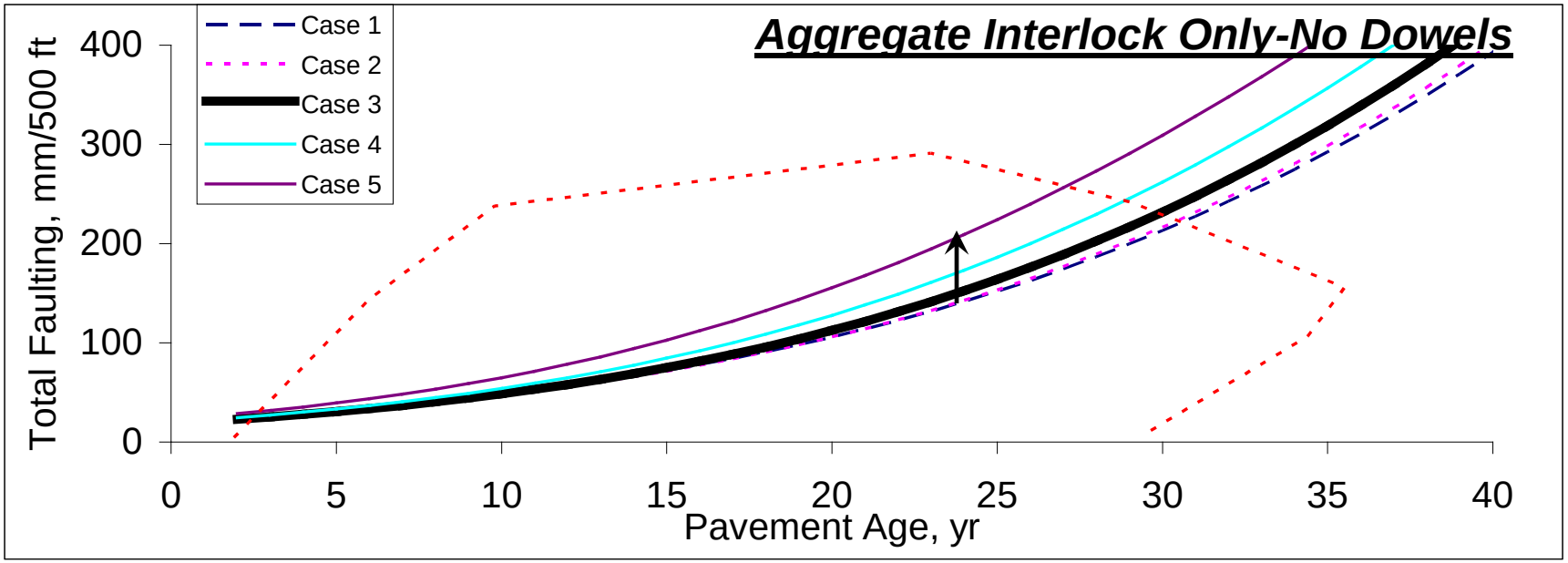
Varying Slab Up-Warp from Average to High

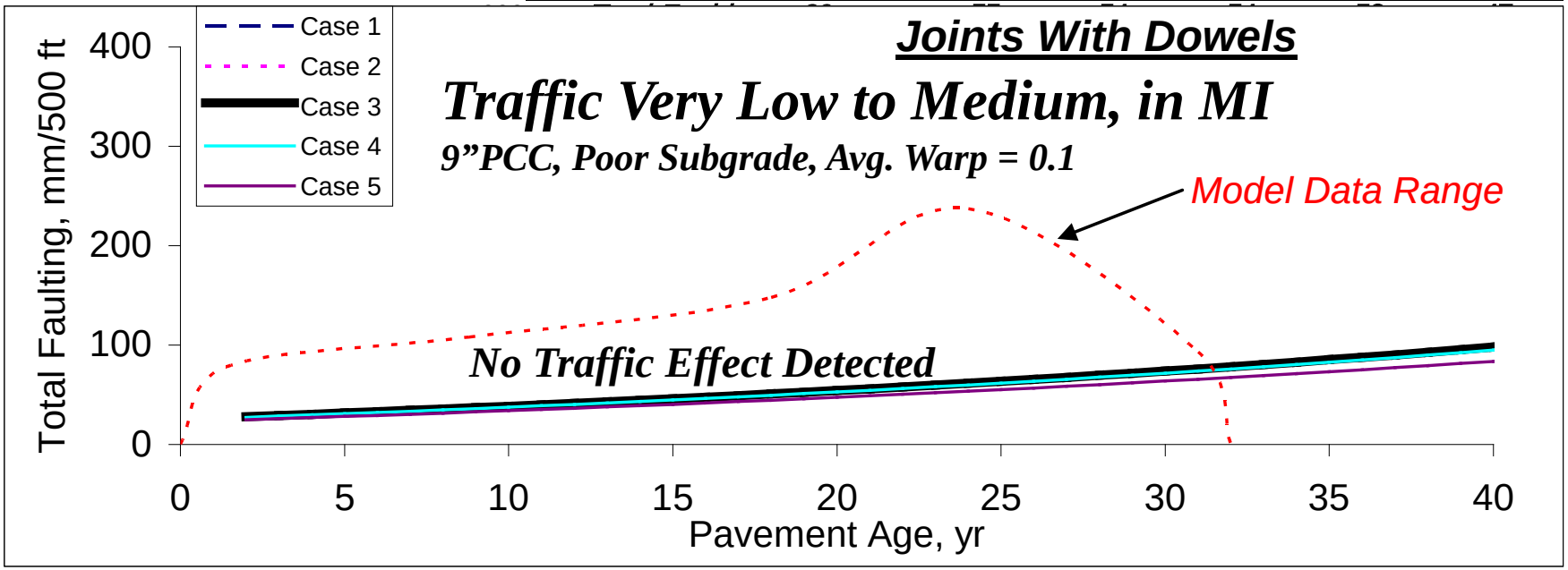
INPUT DATA	Case 1	Case 2	Case 3	Case 4	Case 5
Slab Curvature, ft^{-1} x 1000	0.1	0.15	0.2	0.25	0.3
PCC thickness, in.	11	11	11	11	11
PCC E-modulus, psi	4700000	4700000	4700000	4700000	4700000
PCC Split Tensile, psi	600	600	600	600	600
Joint Spacing, ft	20	20	20	20	20
Subgrade Overburden, psf	220	220	220	220	220
Subgrade w%	12	12	12	12	12
Subgrade P200%	25	25	25	25	25
Days with precip/yr	151	151	151	151	151
Freeze Index, degF-days/yr	1211	1211	1211	1211	1211
Ann. Precipitation, in	38	38	38	38	38
Days < 32 degF/yr	164	164	164	164	164
Days > 90 degF/yr	5	5	5	5	5
Initial KESAL/yr	300	300	300	300	300
Traffic Growth Rate, %/yr	0.05	0.05	0.05	0.05	0.05

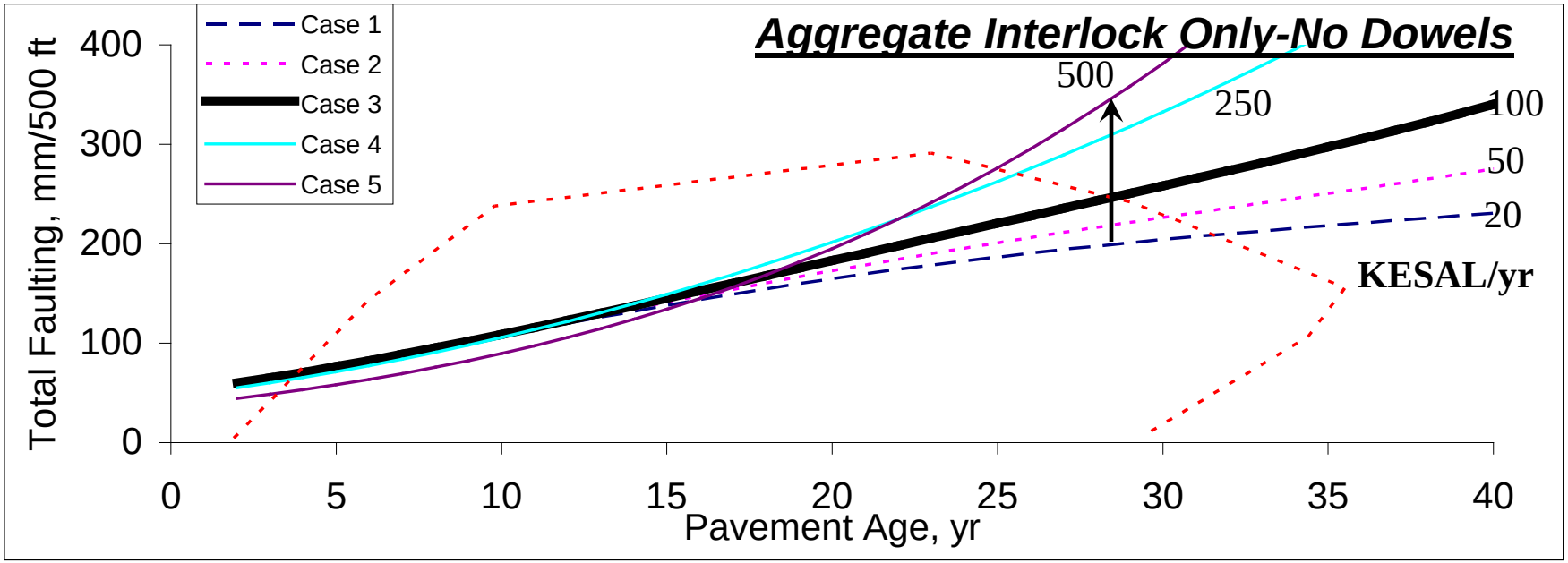

Joints With Dowels
Up-Warp in MI, 0.1 to 0.3
11" PCC, Good Subgrade
Model Data Range
Case 1
Case 2
Case 3
Case 4
Case 5
Total Faulting, mm/500 ft
0
100
200
300
400
0
5
10
15
20
25
30
35
40
Pavement Age, yr

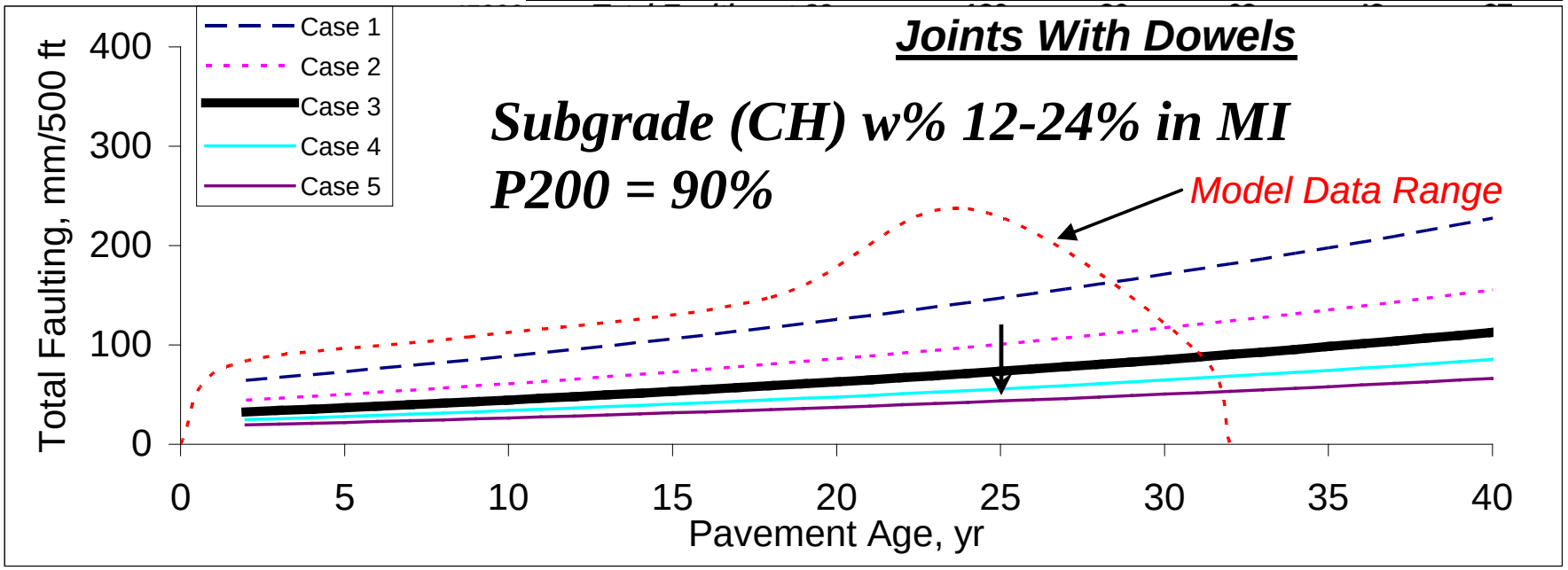

Aggregate Interlock Only-No Dowels
High
Average
Case 1
Case 2
Case 3
Case 4
Case 5
Total Faulting, mm/500 ft
0
100
200
300
400
0
5
10
15
20
25
30
35
40
Pavement Age, yr

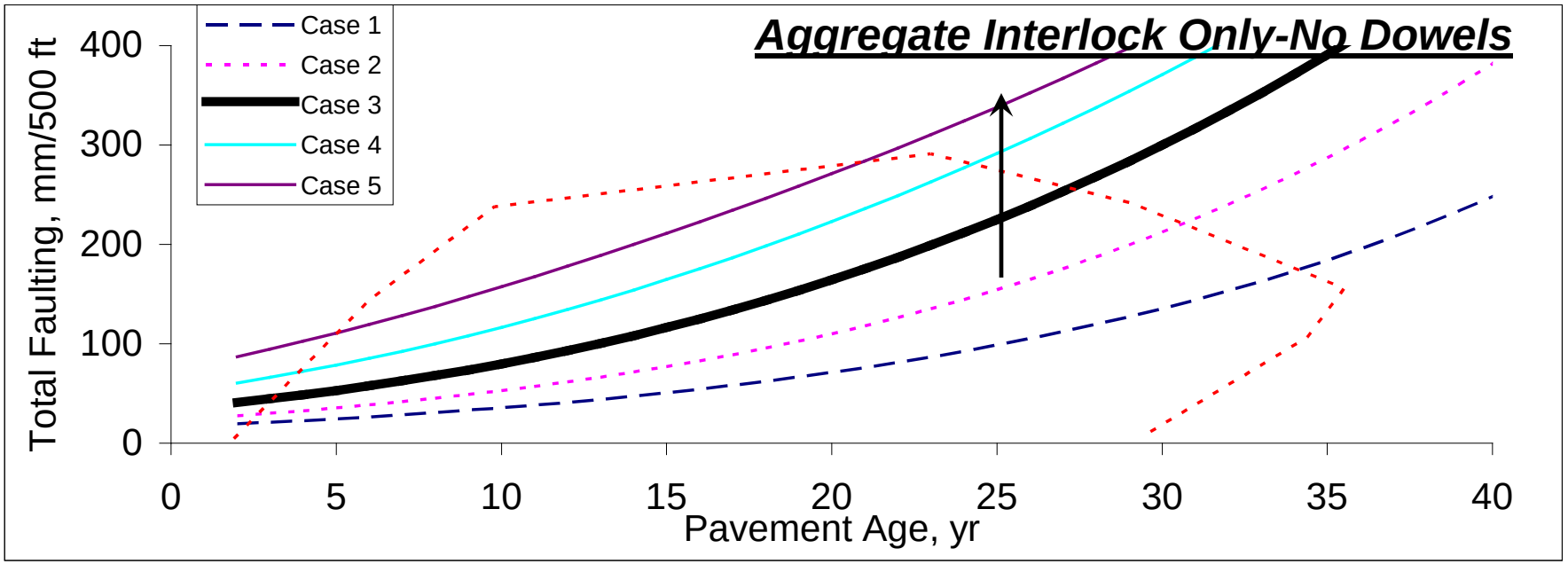

Joints With Dowels
Thickness, 10” to 14” in MI
Clay Subgrade, Significant Up-Warp = 0.2
Model Data Range
Case 1
Case 2
Case 3
Case 4
Case 5
Total Faulting, mm/500 ft
0
100
200
300
400
0
5
10
15
20
25
30
35
40
Pavement Age, yr

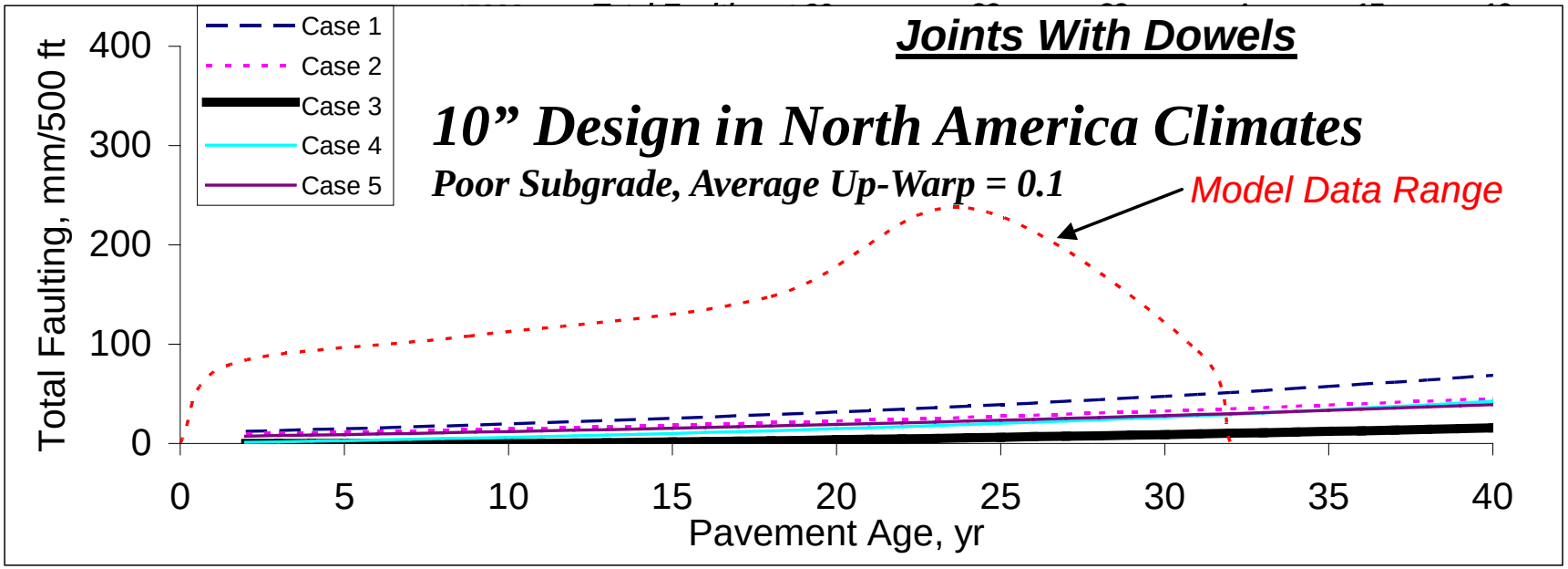

Aggregate Interlock Only-No Dowels
Case 1
Case 2
Case 3
Case 4
Case 5
Total Faulting, mm/500 ft
0
100
200
300
400
0
5
10
15
20
25
30
35
40
Pavement Age, yr

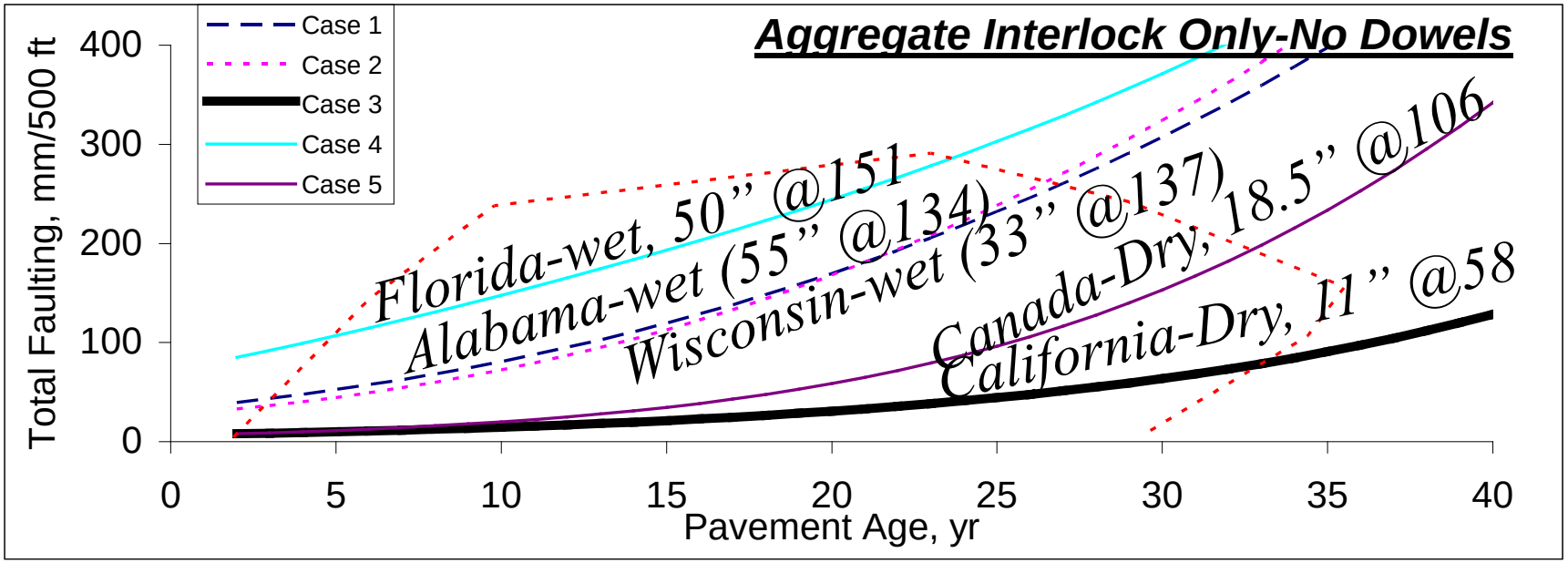

Joints With Dowels
Traffic Very Low to Medium, in MI
9"PCC, Poor Subgrade, Avg. Warp = 0.1
Model Data Range
No Traffic Effect Detected
Case 1
Case 2
Case 3
Case 4
Case 5
Total Faulting, mm/500 ft
Pavement Age, yr
0
100
200
300
400
0
5
10
15
20
25
30
35
40

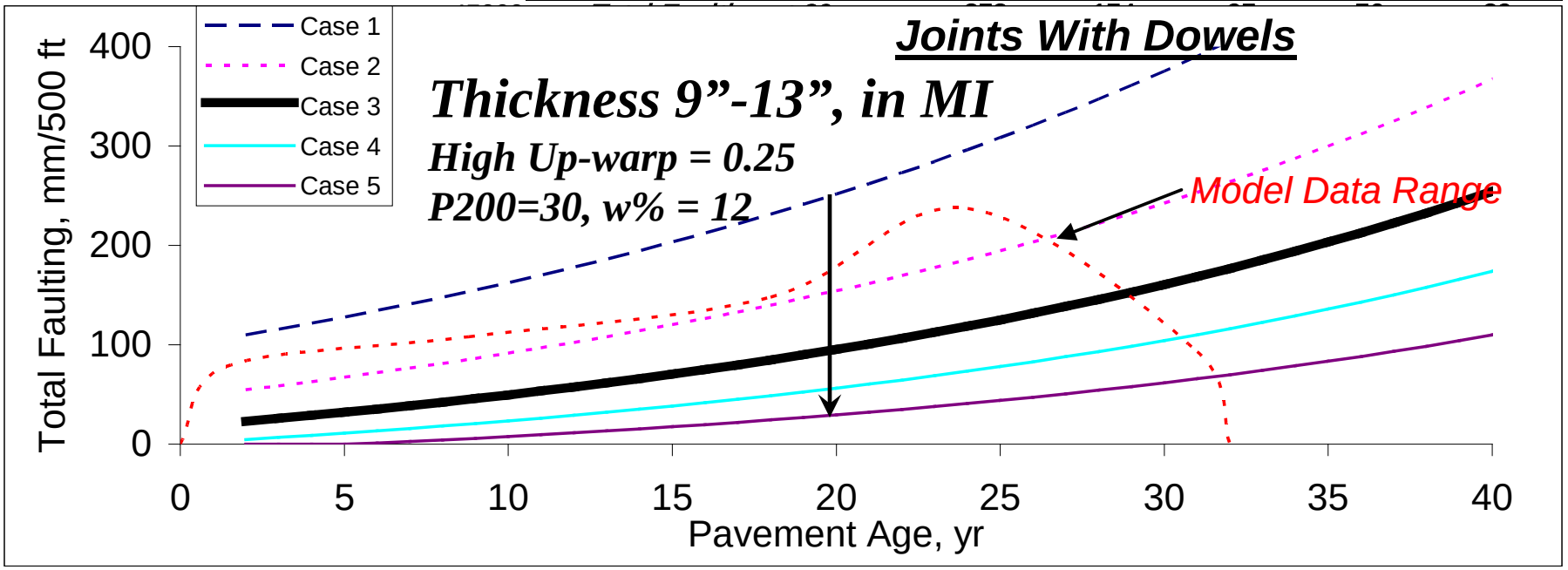

Aggregate Interlock Only-No Dowels
500
250
100
50
20
KESAL/yr
Case 1
Case 2
Case 3
Case 4
Case 5
Total Faulting, mm/500 ft
Pavement Age, yr
0
100
200
300
400
0
5
10
15
20
25
30
35
40

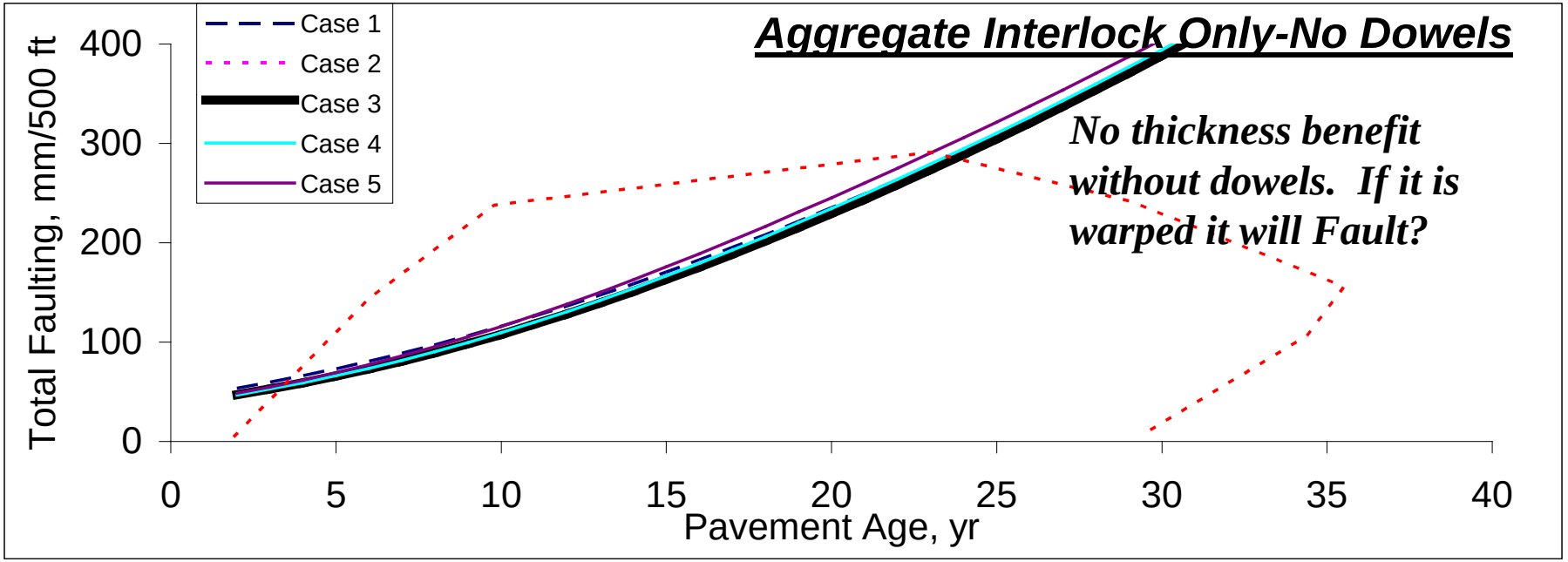

Joints With Dowels
Subgrade (CH) w% 12-24% in MI
P200 = 90%
Model Data Range
Case 1
Case 2
Case 3
Case 4
Case 5
Total Faulting, mm/500 ft
0
100
200
300
400
0
5
10
15
20
25
30
35
40
Pavement Age, yr

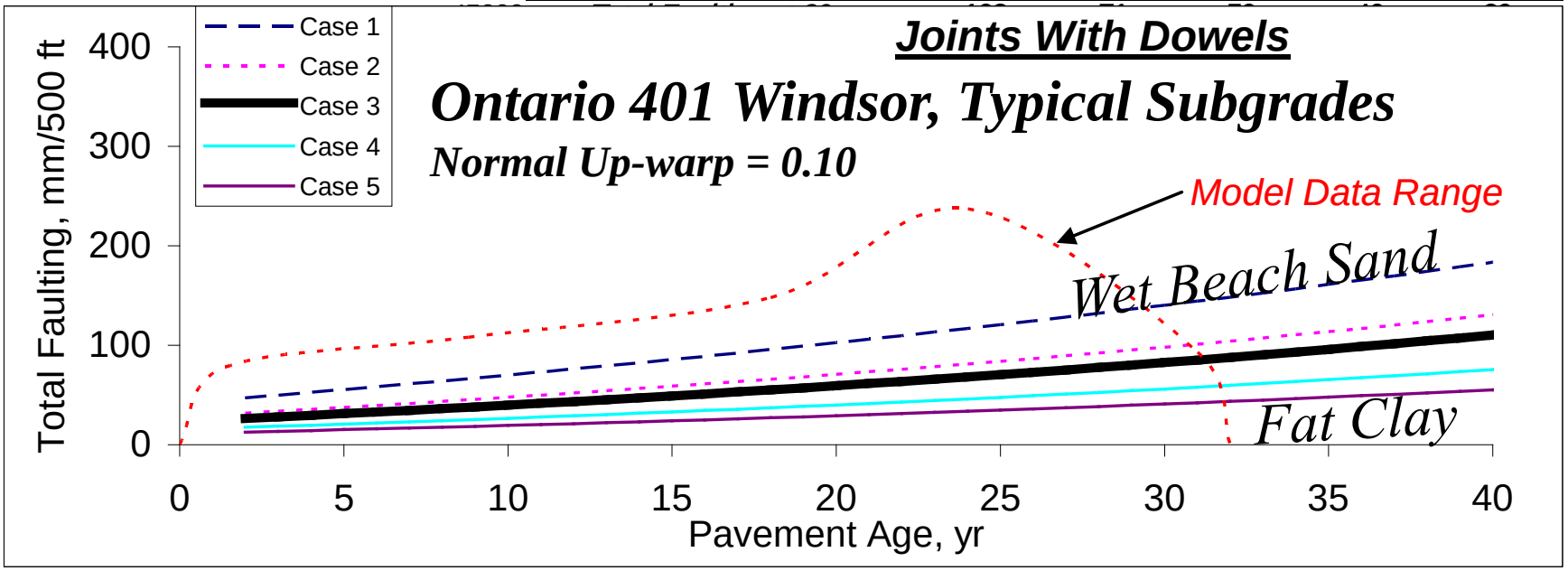

Aggregate Interlock Only-No Dowels
Case 1
Case 2
Case 3
Case 4
Case 5
Total Faulting, mm/500 ft
0
100
200
300
400
0
5
10
15
20
25
30
35
40
Pavement Age, yr

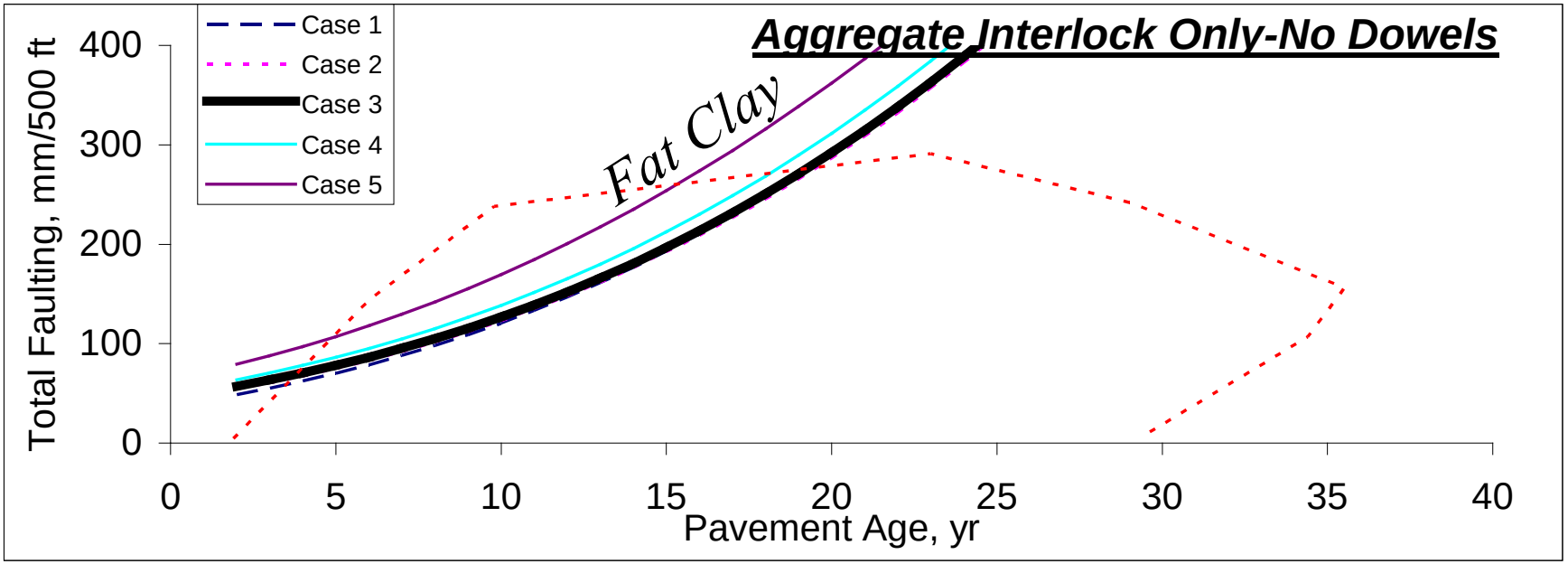

Joints With Dowels
10” Design in North America Climates
Poor Subgrade, Average Up-Warp = 0.1
Model Data Range
Case 1
Case 2
Case 3
Case 4
Case 5
Total Faulting, mm/500 ft
0
100
200
300
400
0
5
10
15
20
25
30
35
40
Pavement Age, yr


Aggregate Interlock Only-No Dowels
Florida-wet, 50” @151
Alabama-wet (55” @134)
Wisconsin-wet (33” @137)
Canada-Dry, 18.5” @106
California-Dry, 11” @58
Case 1
Case 2
Case 3
Case 4
Case 5
Total Faulting, mm/500 ft
0
100
200
300
400
0
5
10
15
20
25
30
35
40
Pavement Age, yr

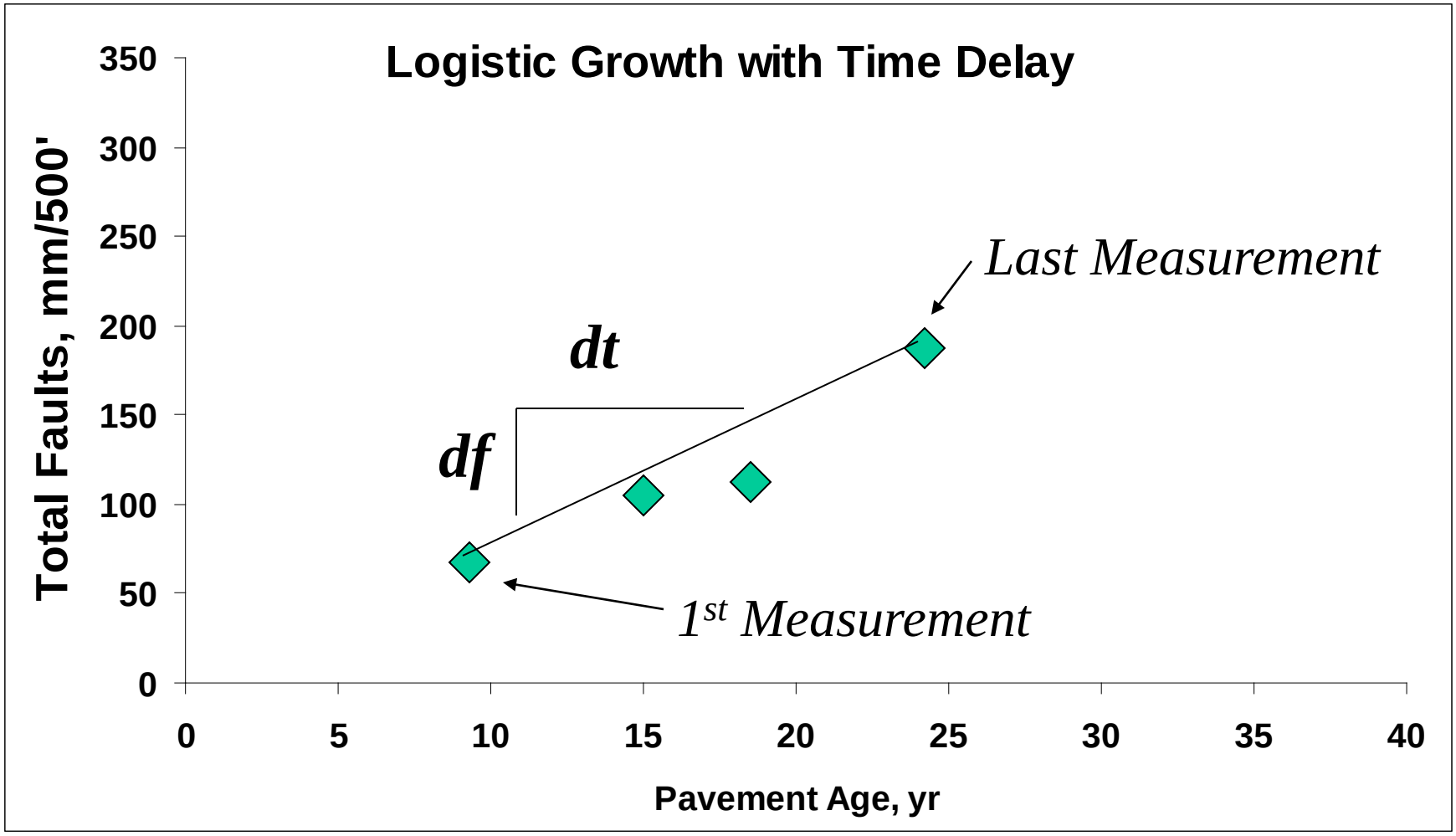

Joints With Dowels
Thickness 9”-13”, in MI
High Up-warp = 0.25
P200=30, w% = 12
Model Data Range
Case 1
Case 2
Case 3
Case 4
Case 5
Total Faulting, mm/500 ft
Pavement Age, yr
0
100
200
300
400
0
5
10
15
20
25
30
35
40


Aggregate Interlock Only-No Dowels
No thickness benefit without dowels. If it is warped it will Fault?
Case 1
Case 2
Case 3
Case 4
Case 5
Total Faulting, mm/500 ft
Pavement Age, yr
0
100
200
300
400
0
5
10
15
20
25
30
35
40


Joints With Dowels
Ontario 401 Windsor, Typical Subgrades
Normal Up-warp = 0.10
Model Data Range
Wet Beach Sand
Fat Clay
Case 1
Case 2
Case 3
Case 4
Case 5
Total Faulting, mm/500 ft
0
100
200
300
400
0
5
10
15
20
25
30
35
40
Pavement Age, yr


Aggregate Interlock Only-No Dowels
Fat Clay
Case 1
Case 2
Case 3
Case 4
Case 5
Total Faulting, mm/500 ft
0
100
200
300
400
0
5
10
15
20
25
30
35
40
Pavement Age, yr

Faulting Rates



Faulting Rate Index Values

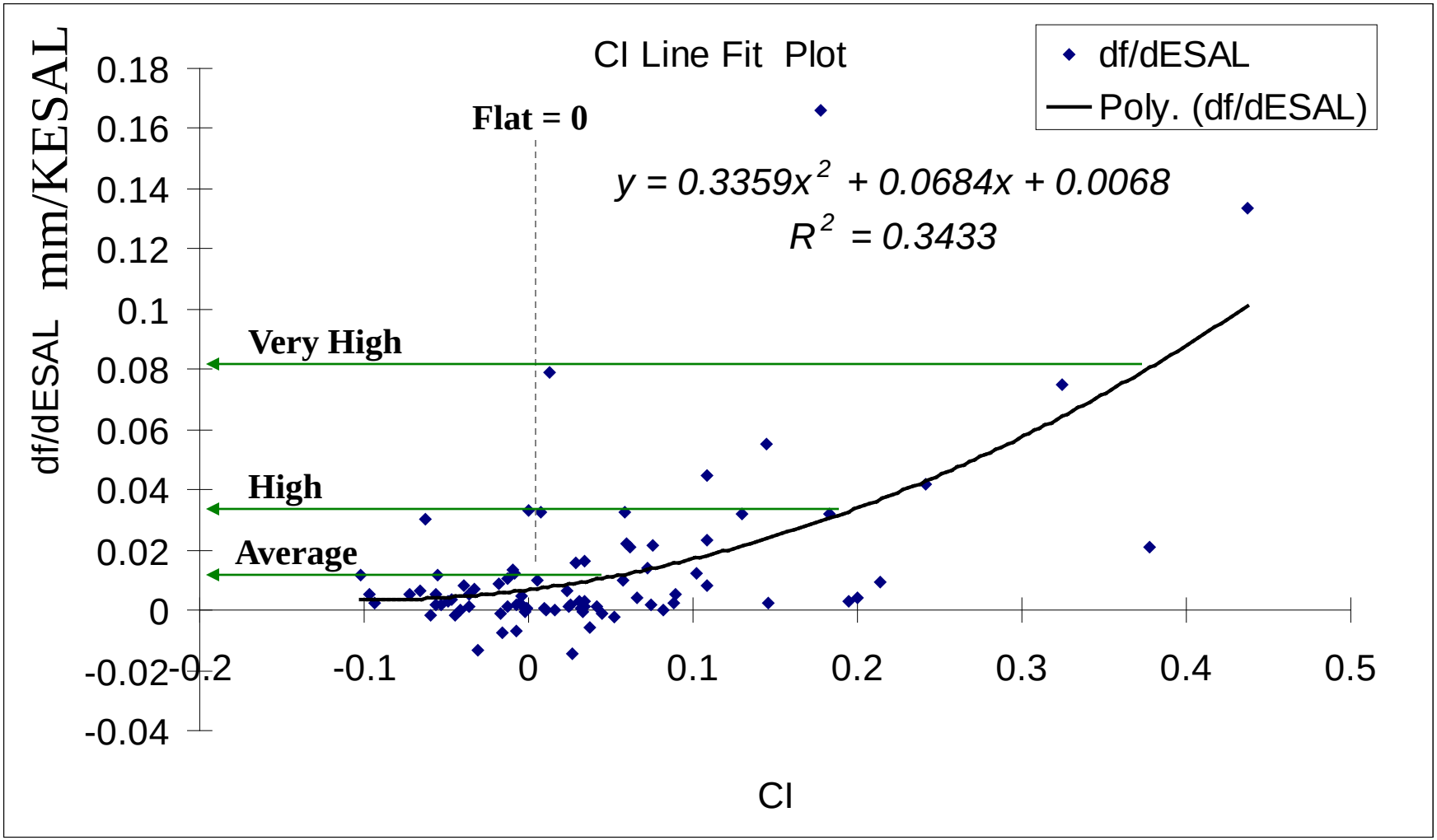
df/dt = Growth per year

df/dESAL = Growth per KESAL

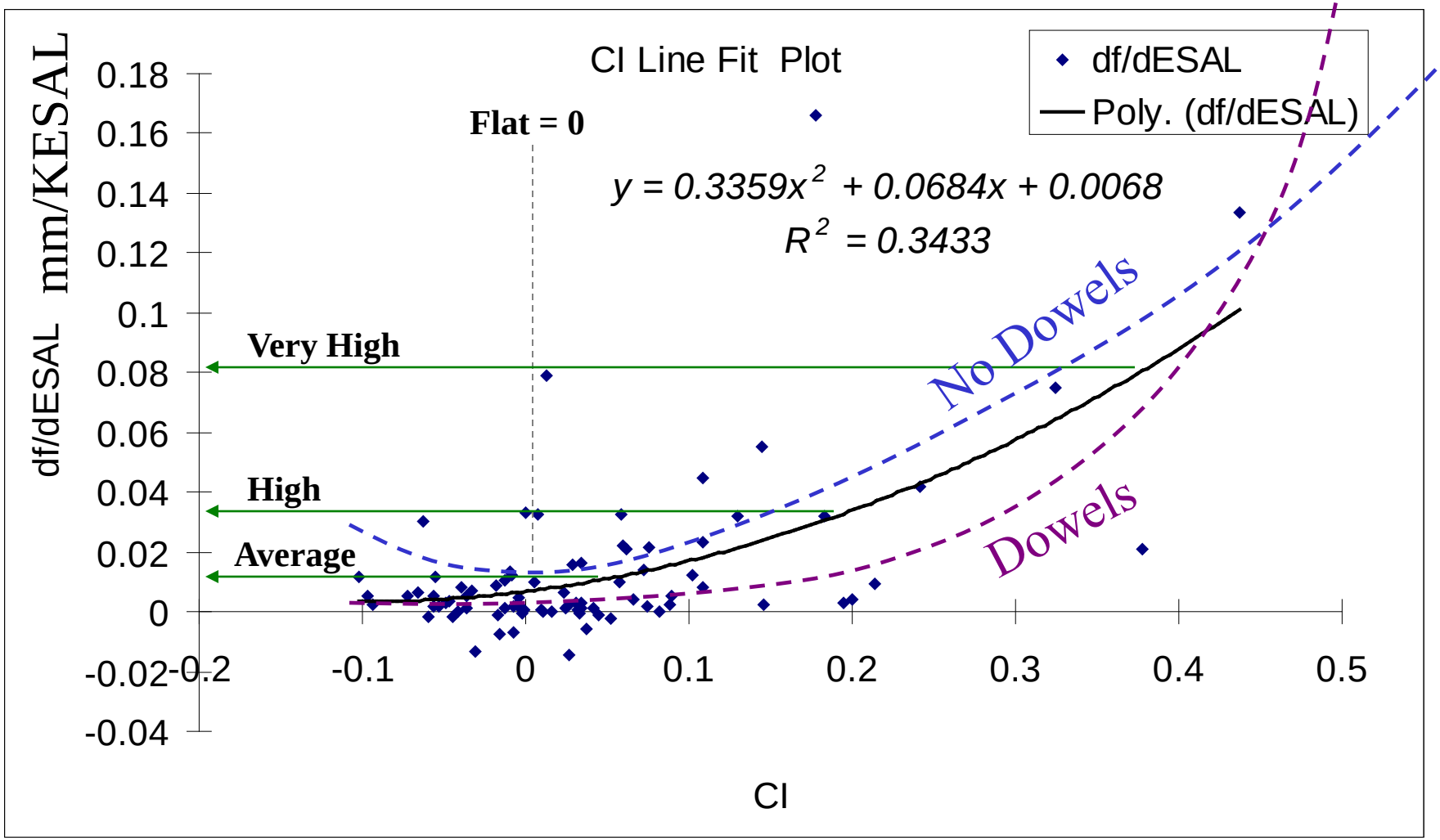
Both use… “Last – First” divided by change in time, or KESAL

Parameter	*df/dt*	*df/dESAL*
df/dt	1.000	
df/dESAL	0.621	1.000
Initial KESAL/yr	-0.100	-0.280
CumTrf	-0.049	-0.352
AnnPrecip	-0.050	-0.088
Days32	0.234	0.347
Days90	-0.175	-0.313
DaysWet	0.041	0.072
Freeze Thaw Cycles/yr	0.142	0.204
FZI	0.268	0.422
PCCThick	-0.178	-0.262
BASE Thickness, in	0.034	-0.112
Subgrade LL	0.011	0.054
Subgrade PL	-0.006	0.109
P200	0.065	0.145
W%	0.060	0.032
JtSp	-0.119	-0.133
Dowel_Diameter, in	-0.371	-0.261
PCC Unit wt.	0.101	0.116
EMOD	0.258	0.338
SplitT	0.077	-0.043
CI	0.550	0.550

Parameter	*df/dESAL*
df/dESAL	1.000
P200/Po	0.280
INIKESAL/PCCthick^3	-0.197
(DaysWet/Po)	0.172
(FZI+1)/Po	0.485
JtSpace*CI	0.538
DowDia+.1	-0.261
(EMOD)/(SplitT)	0.352
(Days32+1)/Po	0.444
GAP = CI/1000*6*(JtSp/2)^2	0.509
GAP*DaysWet*(FZI+1)	0.657
minutes per ESAL	0.413
GAP/(min per ESAL)	0.224
GAP*P200/Po	0.506
PCCThick+BaseThickness	-0.195
(10+PI)/Po	0.173



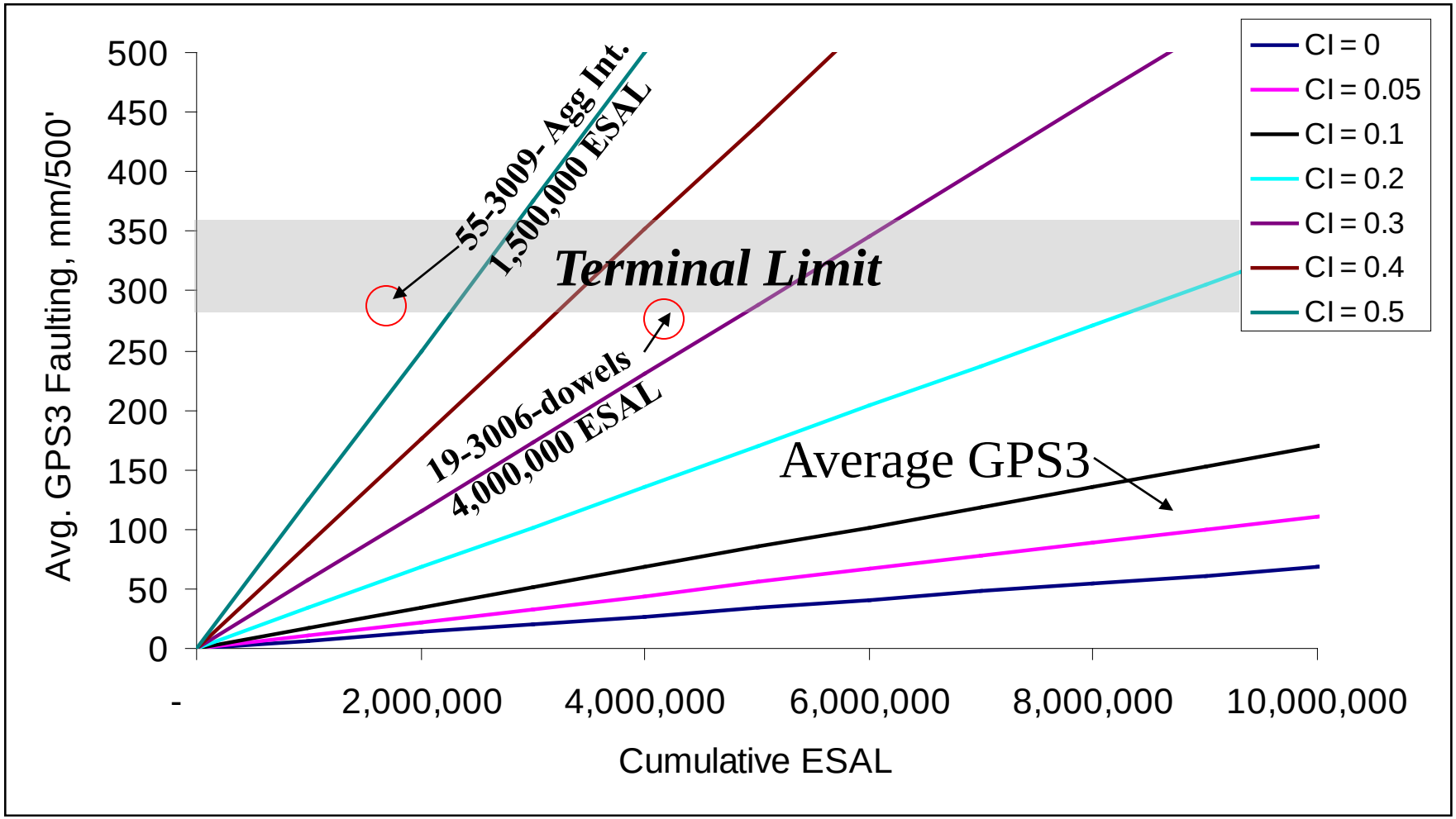
Overall Population Trend
1 Data Point per GPS3 Site
***Each Cross Section has Unique Trend Shape**



Overall Population Trend

1 Data Point per GPS3 Site

***Each Cross Section has Unique Trend Shape**



Overall Population Trend
1 Data Point per GPS3 Site
***Each Cross Section has Unique Trend Shape**

CONCLUSIONS

Rapid Travel Profile Data is Great For Faulting Analysis

These are among the best Faulting Prediction models ever established and can be used as a design check.

Non-linear models are more sensitive to "*Garbage-In = Garbage-out*. Must use rational climate and subgrade value sets.

Non-linear models are more sensitive at the data set boundaries, and extrapolation zones.

CONCLUSIONS

High Performance Paving Concrete should have high strain capacity, which is relatively low elastic modulus for a given tensile strength value, i.e. "***Flexible Concrete***" .

More Freezing and More Days with Precipitation per year are key factors causing more faulting. Worst case is high slab up-warp with high precipitation, over more days per year, with colder climate.

Past Design Methods handled Traffic and Subgrade Well, but not Climate.

CONCLUSIONS

High Up-Warp is the Precursor to Rapid Faulting.

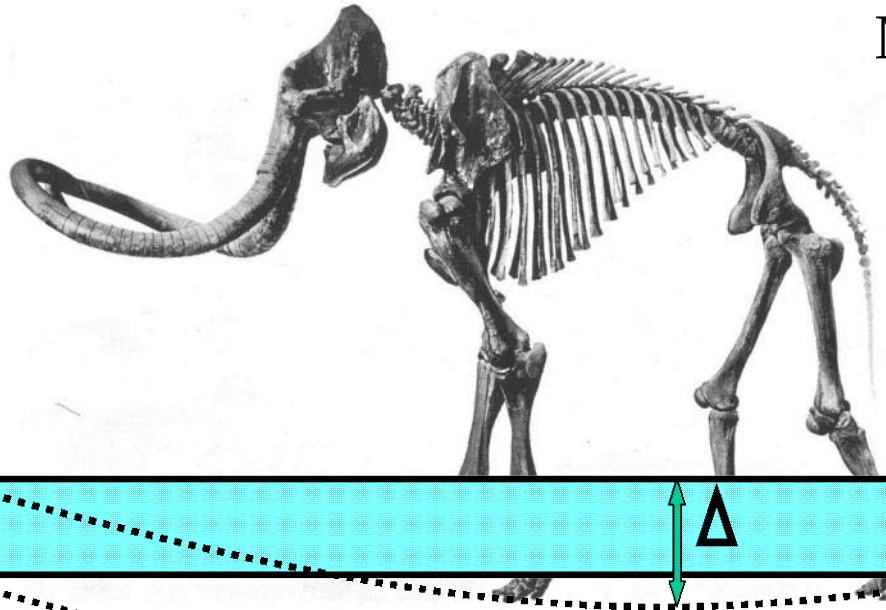
Warp is The Most Correlated Parameter in LTPP GPS3.

Remember Hveem?, California Desert Concrete Paving Research, Sand Equivalency Test, Shrinkage Rings, Low Heat Cement, Thermal Shock, Bonded Base…..

Minimize the Warp-Ability of Your Concrete Designs.

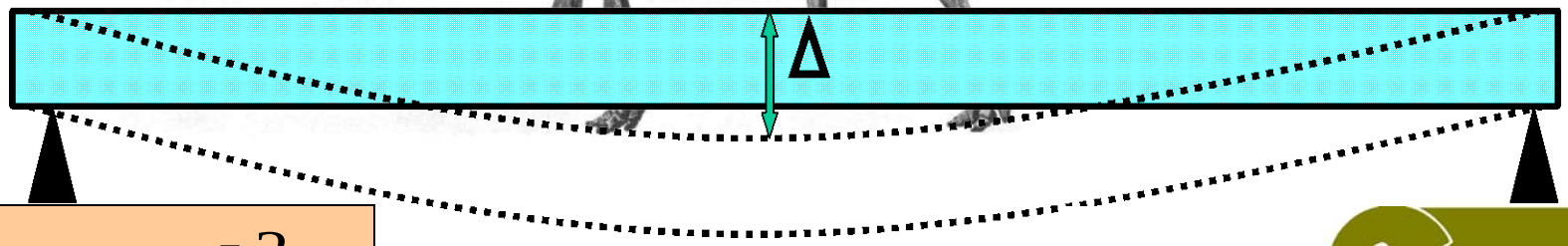
It Will Be Worth It.

From Michigan, Good Luck

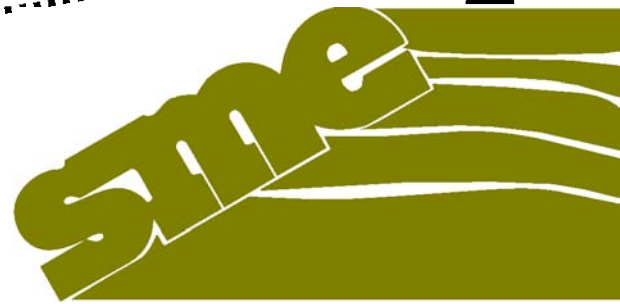


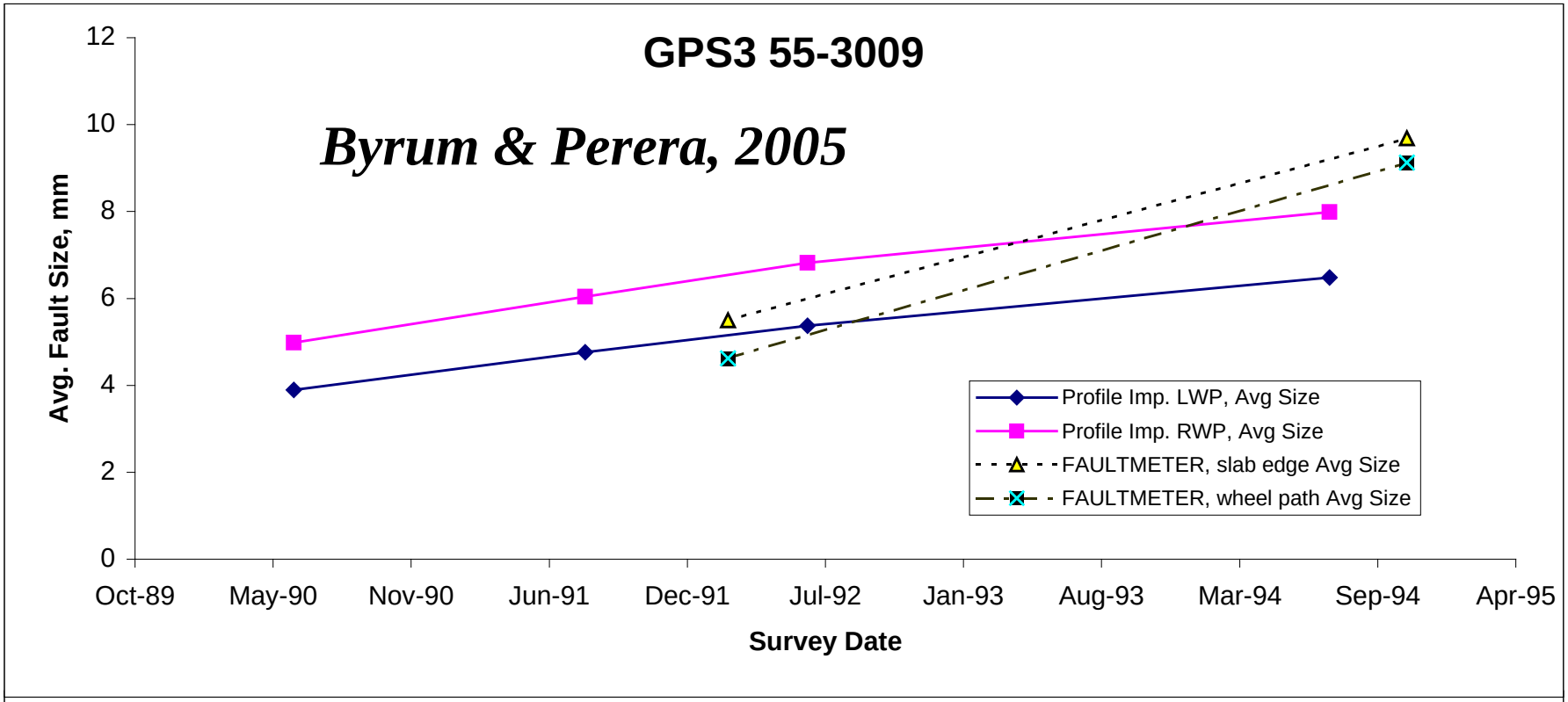
Michigan's State Fossil:

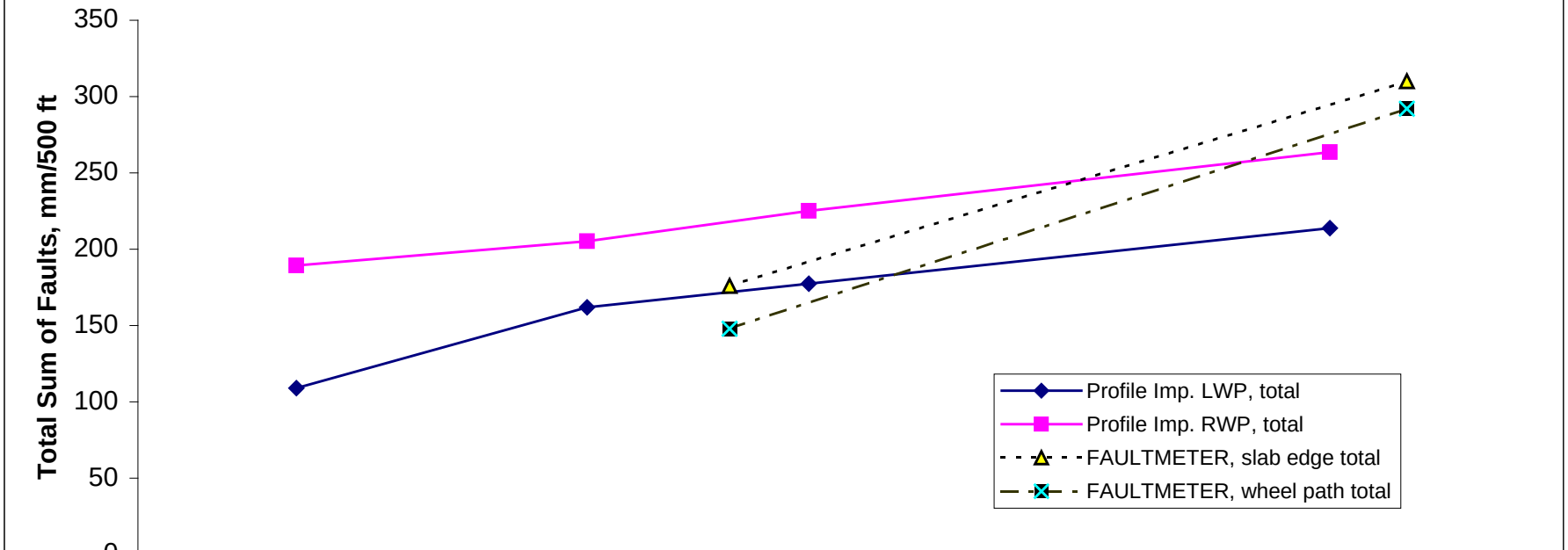
Mastodon

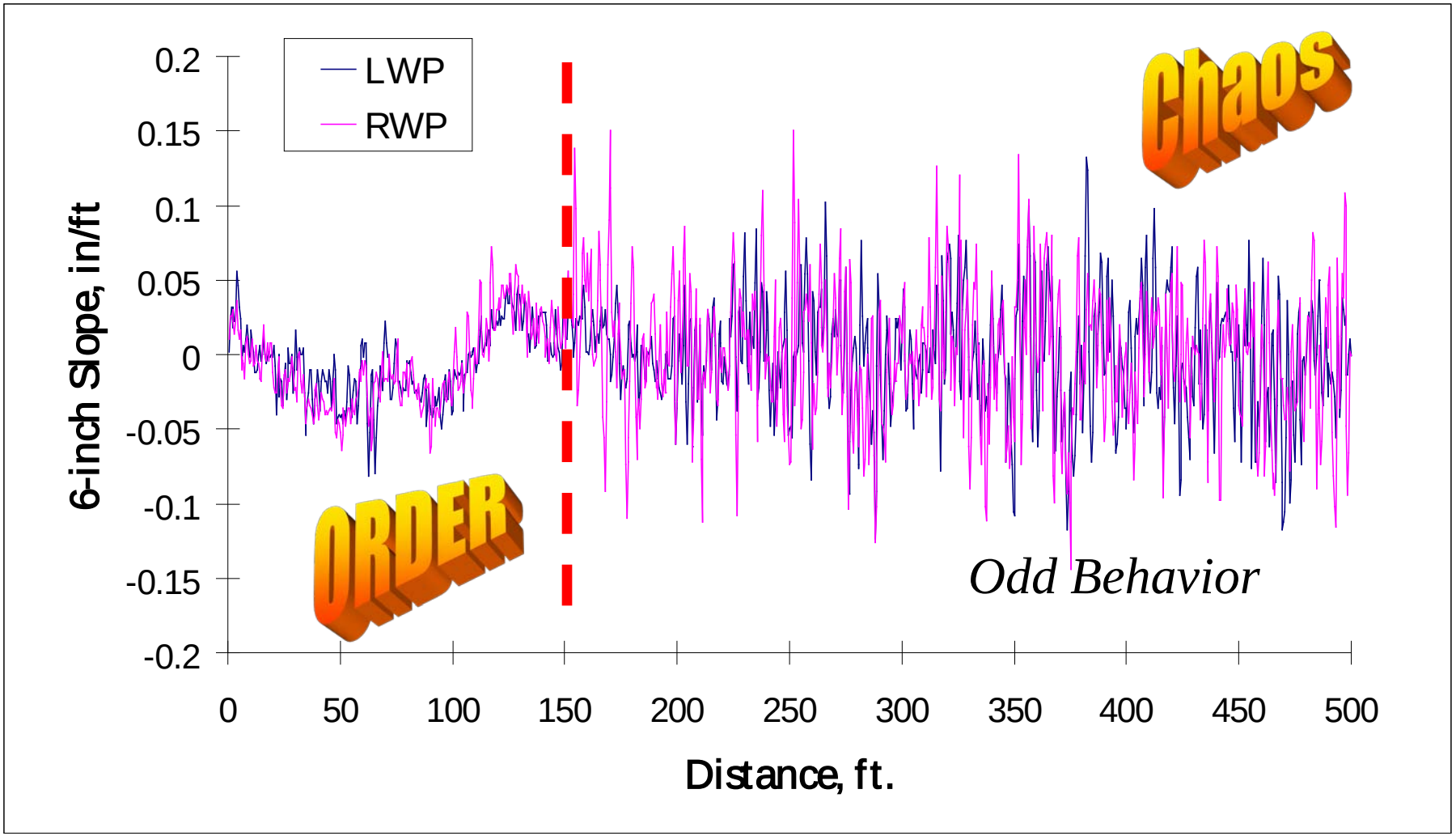


$$M = EI\frac{d^2z}{dx^2}$$

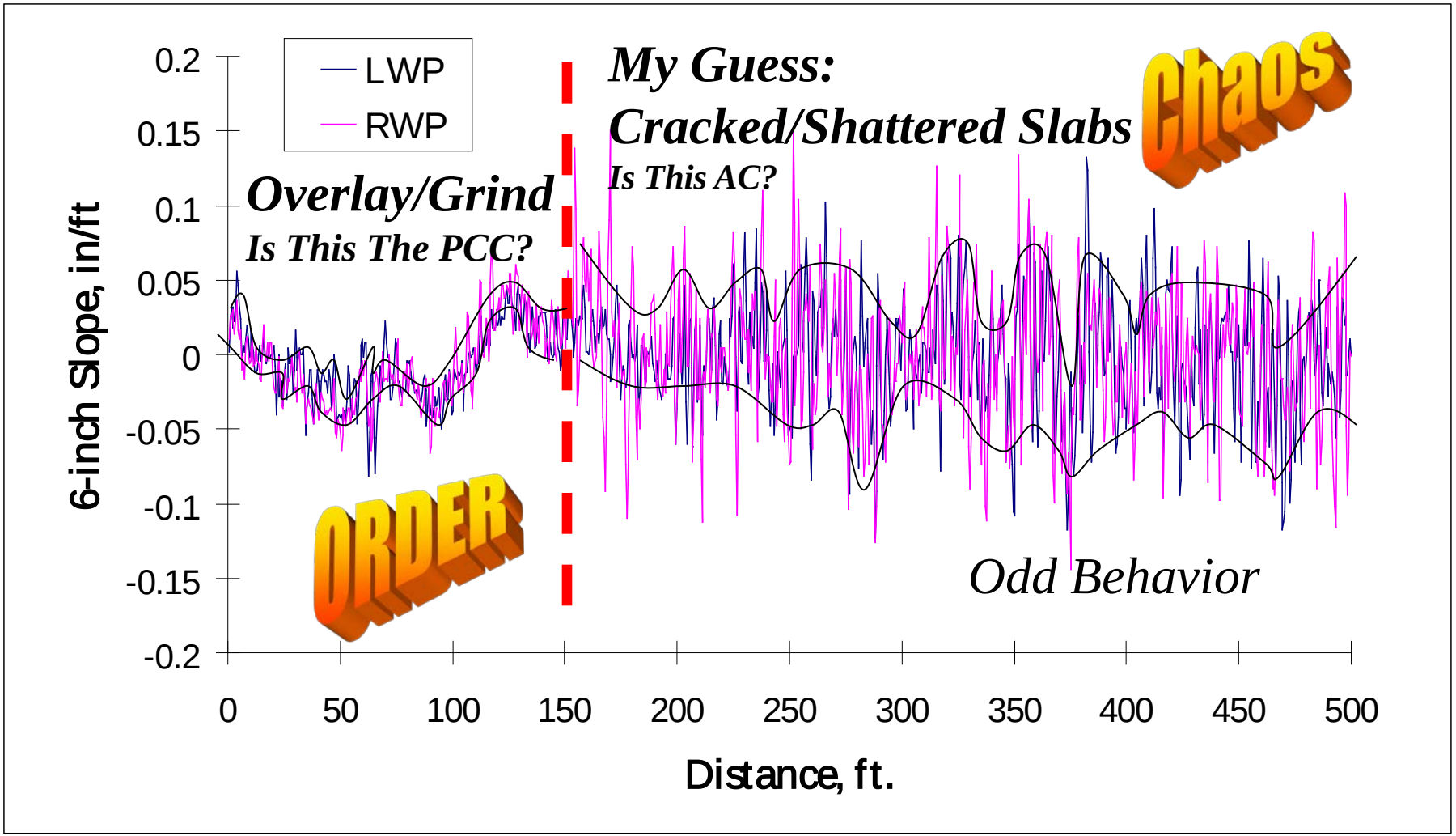



GPS3 55-3009
Byrum & Perera, 2005
Avg. Fault Size, mm
0
2
4
6
8
10
12
Oct-89
May-90
Nov-90
Jun-91
Dec-91
Jul-92
Jan-93
Aug-93
Mar-94
Sep-94
Apr-95
Survey Date
Profile Imp. LWP, Avg Size
Profile Imp. RWP, Avg Size
FAULTMETER, slab edge Avg Size
FAULTMETER, wheel path Avg Size


Total Sum of Faults, mm/500 ft
0
50
100
150
200
250
300
350
Profile Imp. LWP, total
Profile Imp. RWP, total
FAULTMETER, slab edge total
FAULTMETER, wheel path total

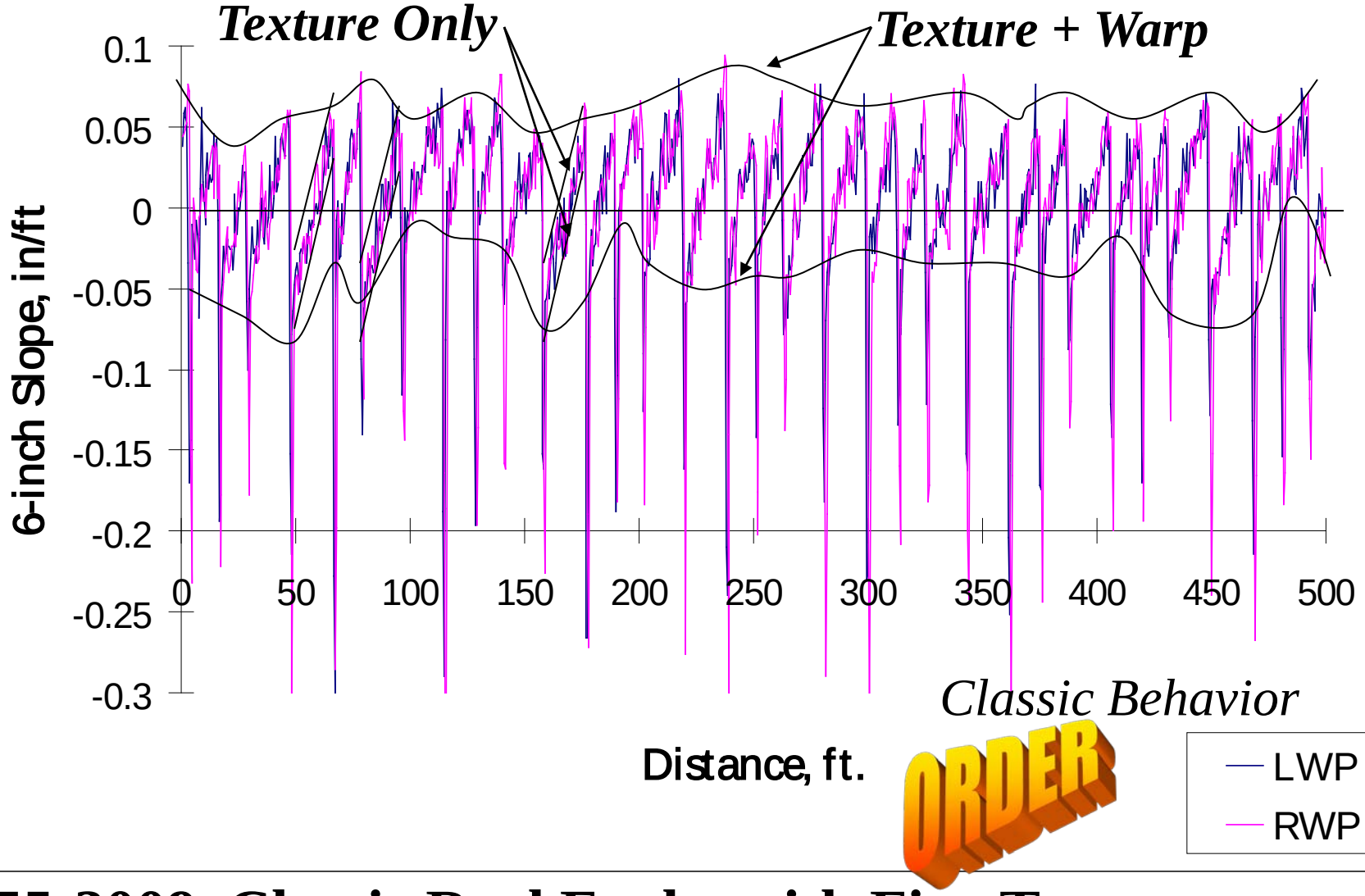


12-4019, Unusual Finishing, Very Coarse Texture, Shattered Slabs ????? Questionable



12-4019, Unusual Finishing, Very Coarse Texture, Shattered Slabs ????? Questionable

Real Faults are Down-Slopes



55-3009 Classic Real Faults with Fine Texture