Seismic Performance of Water Pipelines in the August 24 2014 Napa Earthquake

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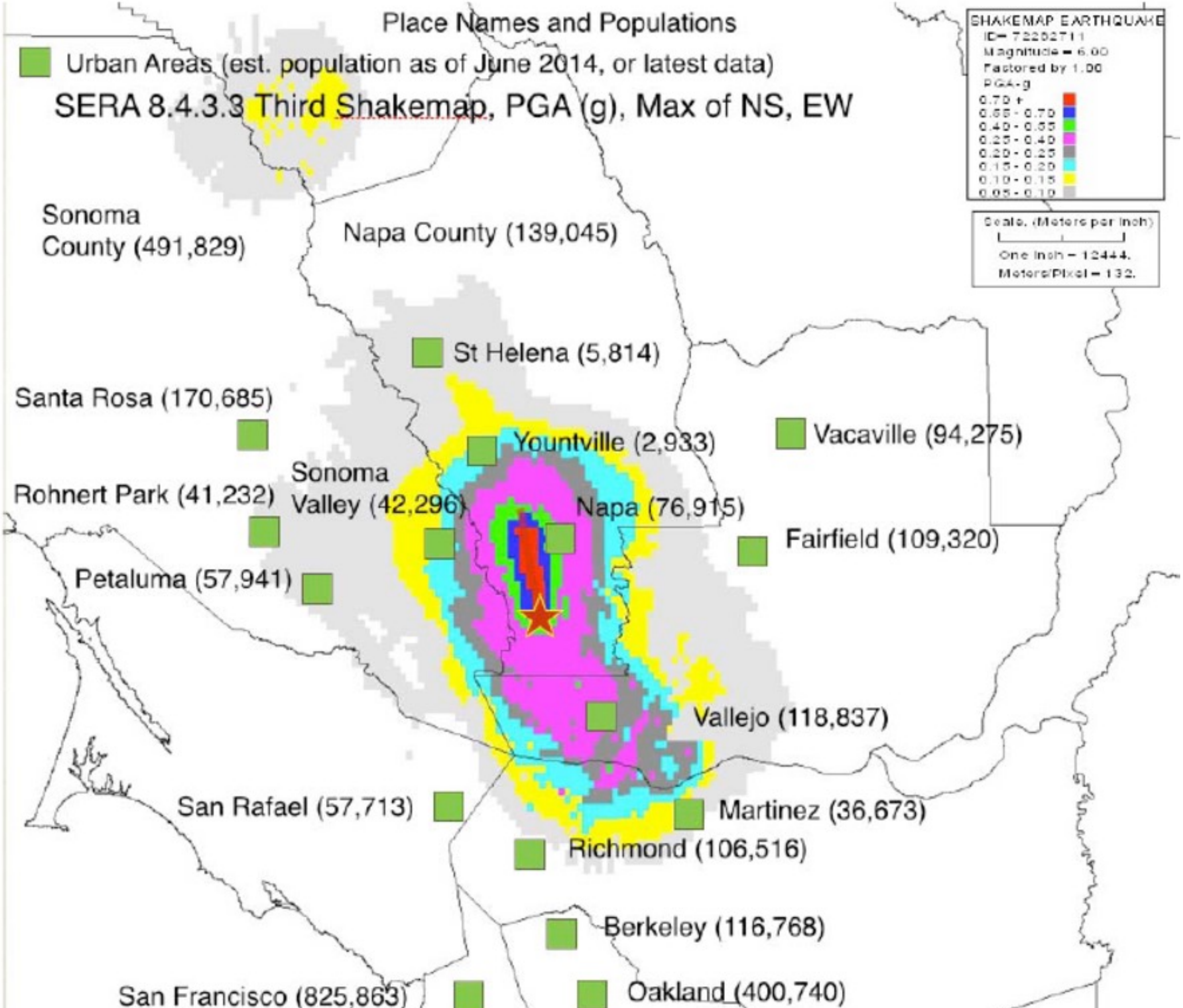
JWWA-WRF-CTWWA Workshop, Sendai, October 2015



Place Names and Populations
Urban Areas (est. population as of June 2014, or latest data)
SERA 8.4.3.3 Third Shakemap, PGA (g), Max of NS, EW
SHAKEMAP EARTHQUAKE
ID= 72282711
Magnitude = 6.00
Factored by 1.00
PGA-g
0.70 +
0.55 - 0.70
0.40 - 0.55
0.25 - 0.40
0.20 - 0.25
0.15 - 0.20
0.10 - 0.15
0.05 - 0.10
Scale. (Meters per Inch)
One Inch = 12444.
Meters/Pixel = 132.
Sonoma County (491,829)
Napa County (139,045)
St Helena (5,814)
Santa Rosa (170,685)
Yountville (2,933)
Vacaville (94,275)
Sonoma Valley (42,296)
Rohnert Park (41,232)
Napa (76,915)
Fairfield (109,320)
Petaluma (57,941)
Vallejo (118,837)
San Rafael (57,713)
Martinez (36,673)
Richmond (106,516)
Berkeley (116,768)
San Francisco (825,863)
Oakland (400,740)

The City of Napa.

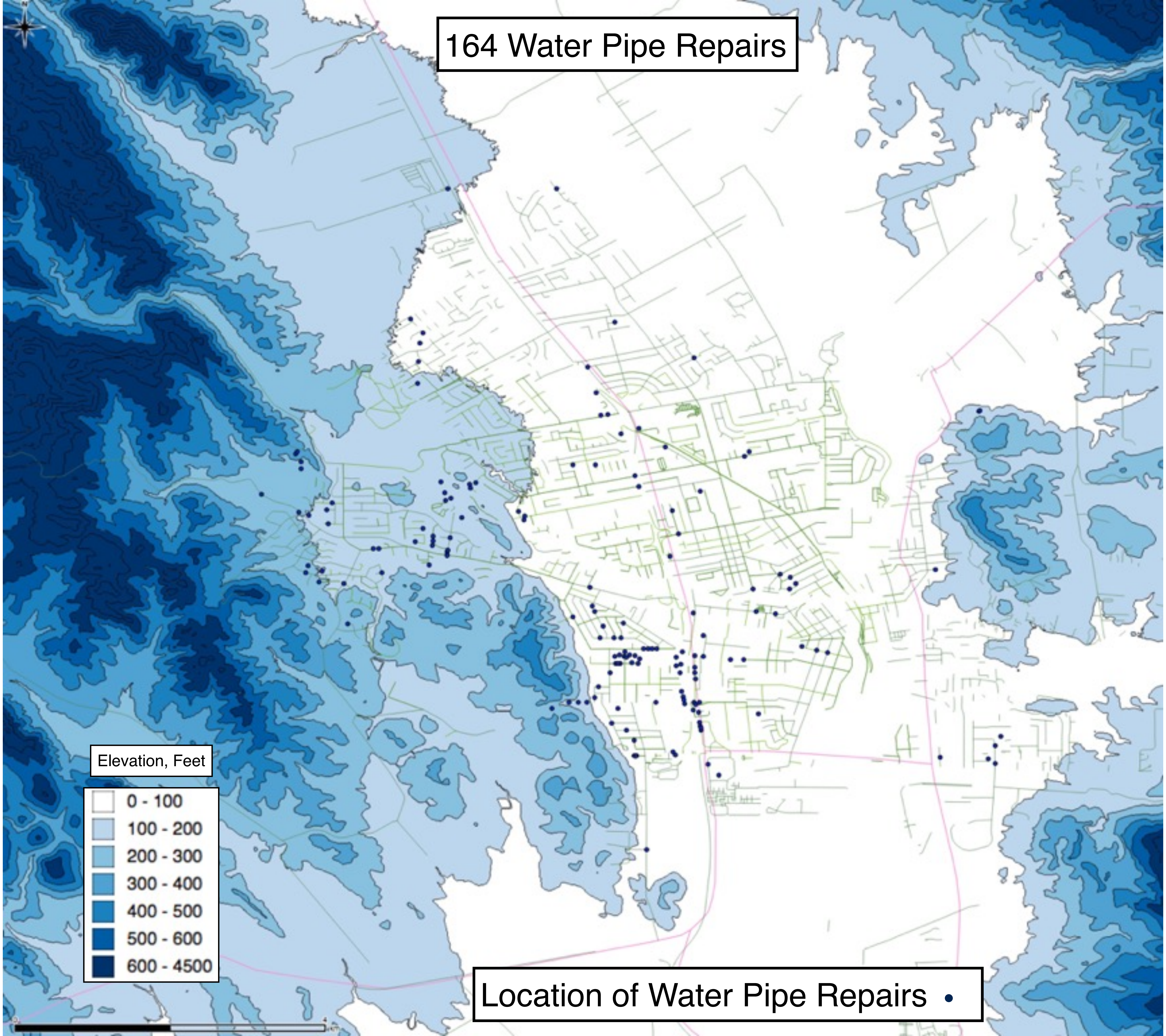
M 6.0 Earthquake on West Side of Town

Population 77,000 people

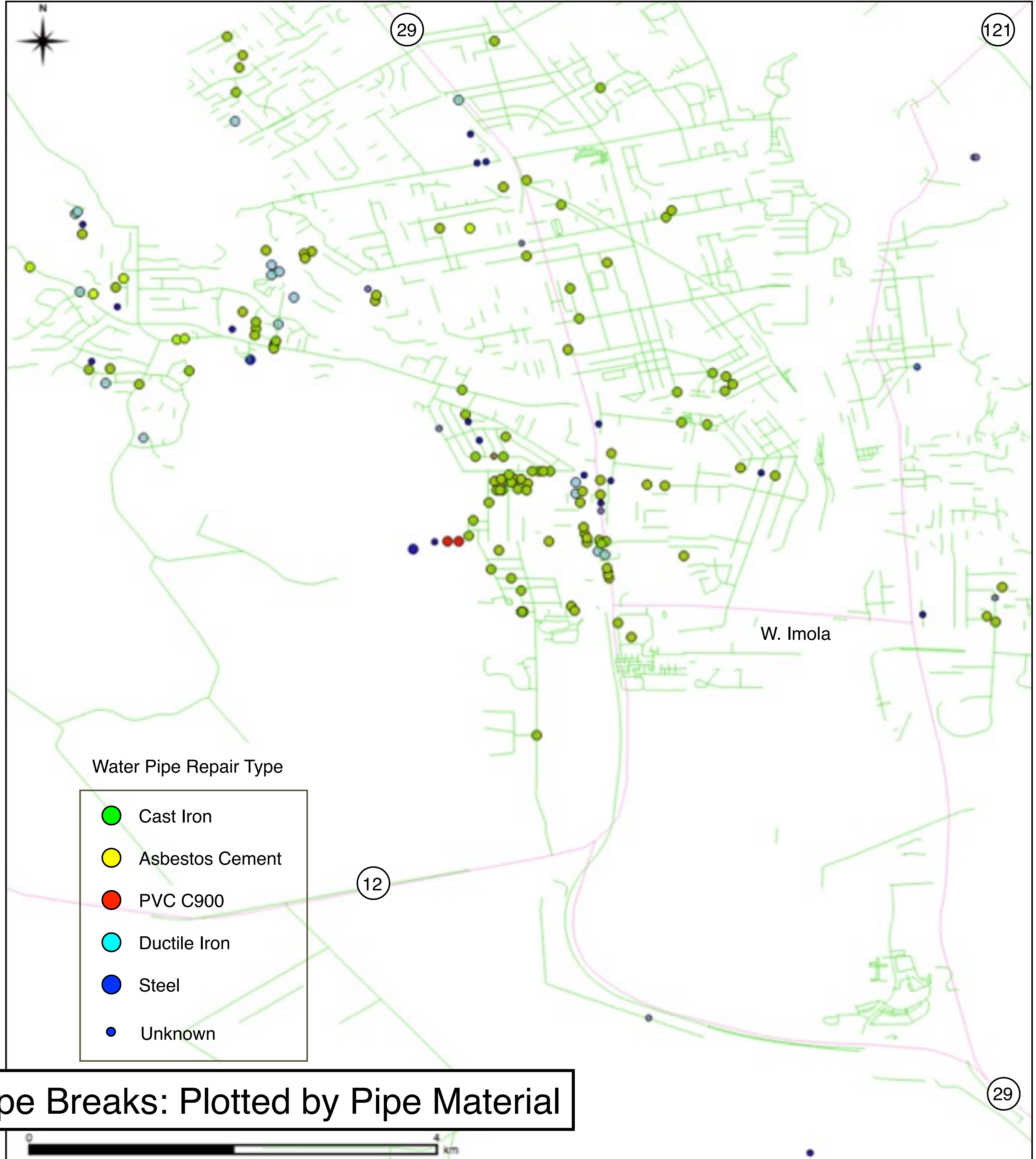
337 Miles (540 km) of Water Pipes, 164 Repairs.

~ Same Length of Gas Pipes, 0 Repairs.
(but some replacement of gas pipes
that crossed the fault after the earthquake)

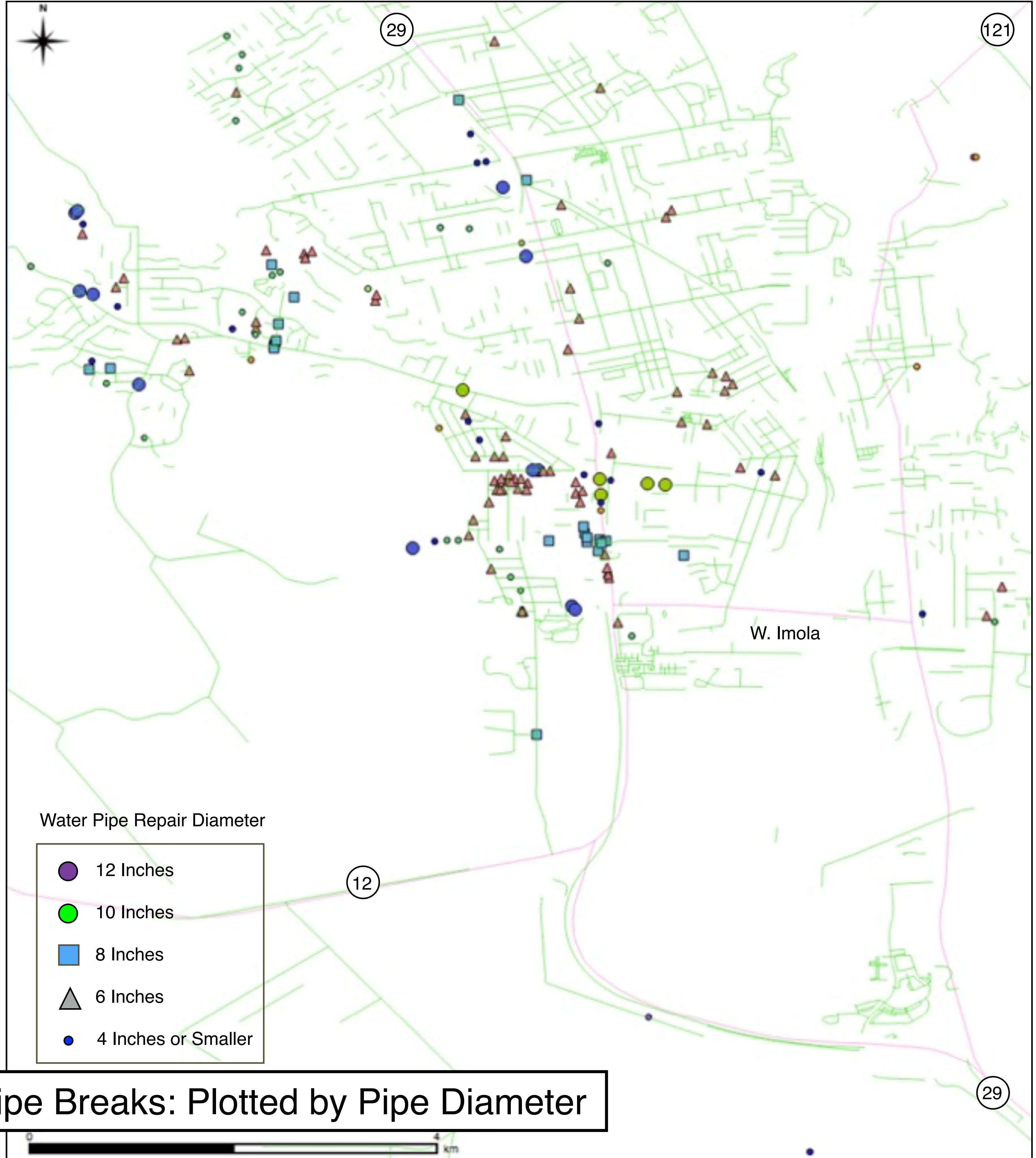
Why?


164 Water Pipe Repairs
Elevation, Feet
0 - 100
100 - 200
200 - 300
300 - 400
400 - 500
500 - 600
600 - 4500
Location of Water Pipe Repairs

Why were there so many Pipe Failures?



164 Water Pipe Breaks: Plotted by Pipe Material



164 Water Pipe Breaks: Plotted by Pipe Diameter

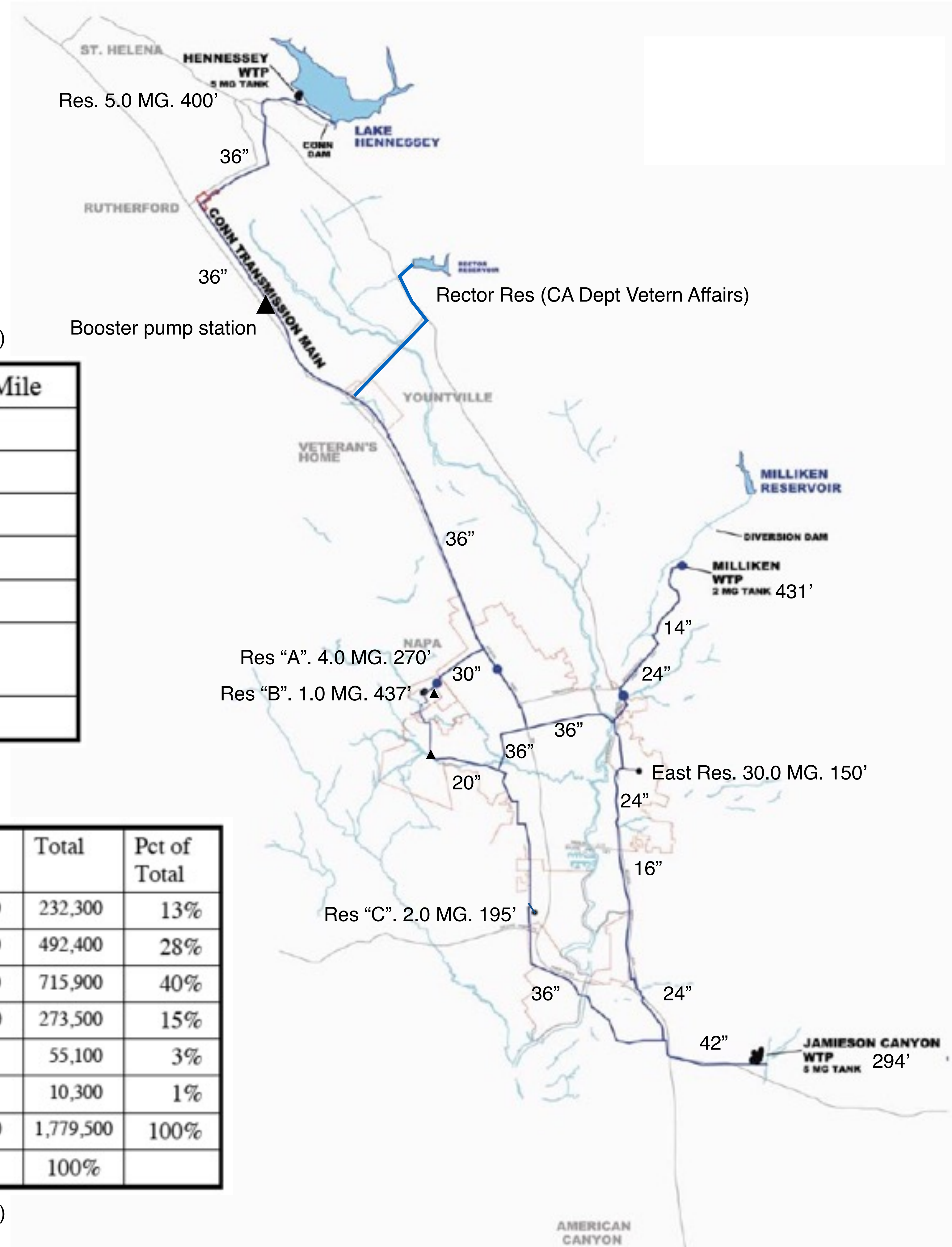
Total Pipe Repairs, By Sept 15 2015 (add 50% Sept-Jan 2015)

Material	Repairs	% Repairs	% Pipe	Repair per Mile
AC	8	5%	10%	0.23
PVC	2	1%	2%	0.34
CI	123	75%	44%	0.82
DI	18	11%	34%	0.16
Steel	3	2%	9%	0.10
Other / unk	7	4%		
Total	163	100%		

Total Pipe Length, 337 Miles

Age (years)	PVC	DI	CI	AC	RCCP	STL	Total	Pct of Total
< 20	6,600	225,600				100	232,300	13%
20-40	24300	370,500	83,400	14,100		100	492,400	28%
40-60		12,300	466,700	167,200	9,900	59,800	715,900	40%
60-80			173,100			100,400	273,500	15%
80-100			55,100				55,100	3%
> 100			10,300				10,300	1%
Total	30,900	608,400	788,500	181,300	9,900	160,400	1,779,500	100%
	2%	34%	44%	10%	1%	9%	100%	

Length of Pipe in Napa Water System (2012, feet)



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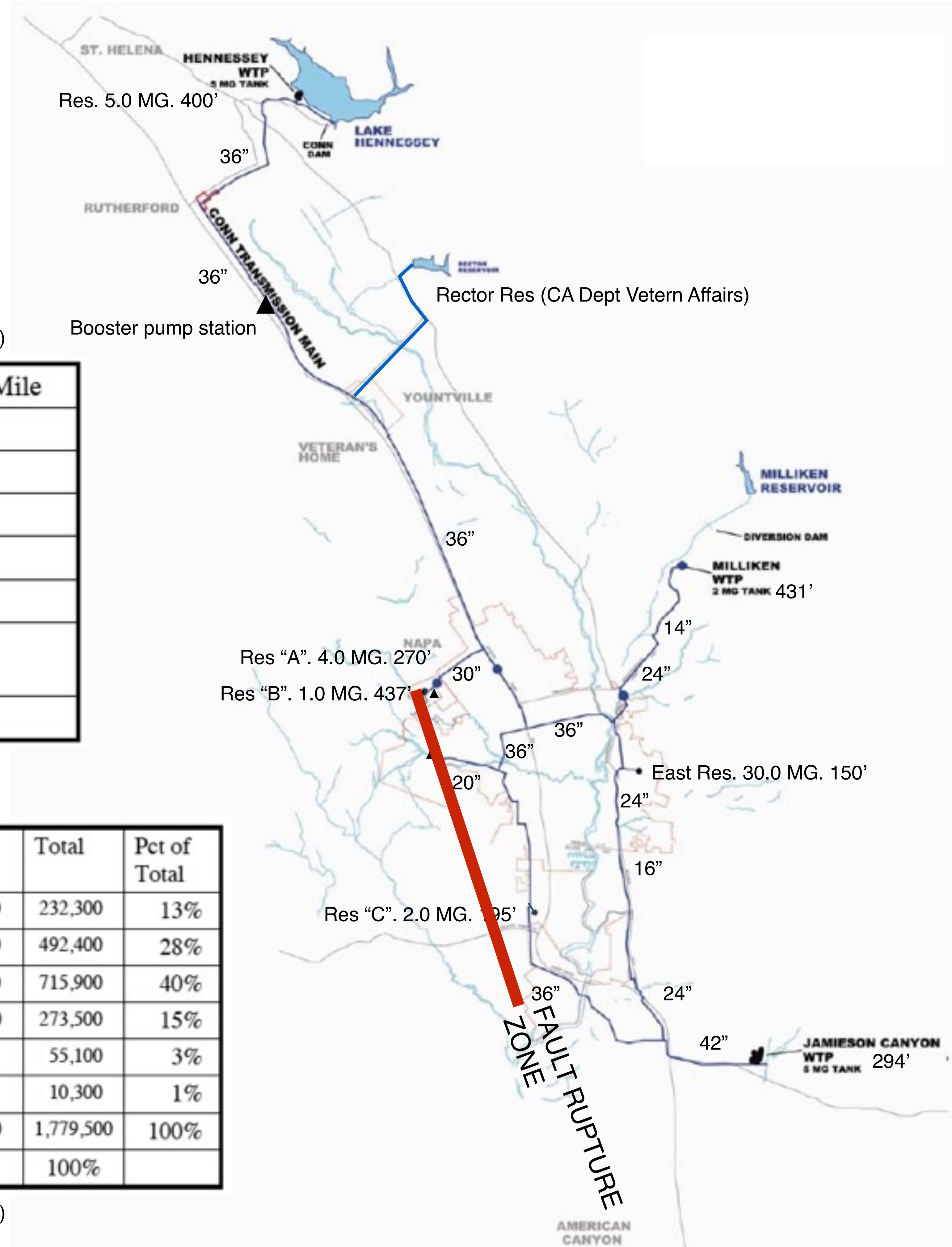
Length of Pipe in Napa Water System (2012, feet)



Sandybrook Lane
Meadowbrook Lane
White Cliff Circle
Twin Oaks Drive
Primary Offset Zone (Line A)

Water Pipe Repair Status

Pipe Repair

PGV, cm/sec

> 85 cm/sec

70 to 85 cm/sec

50 to 70 cm/sec

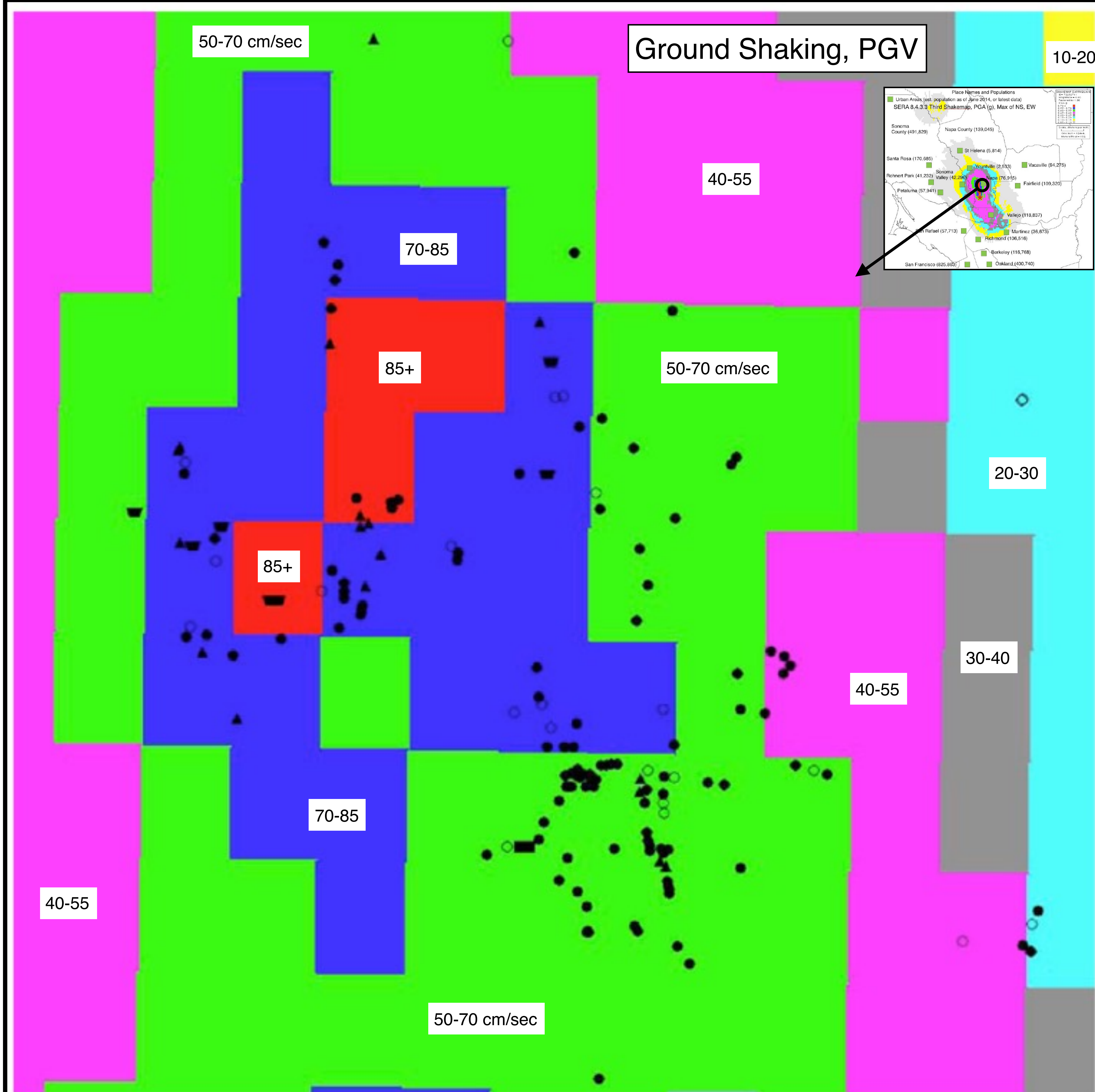
40 to 55 cm/sec

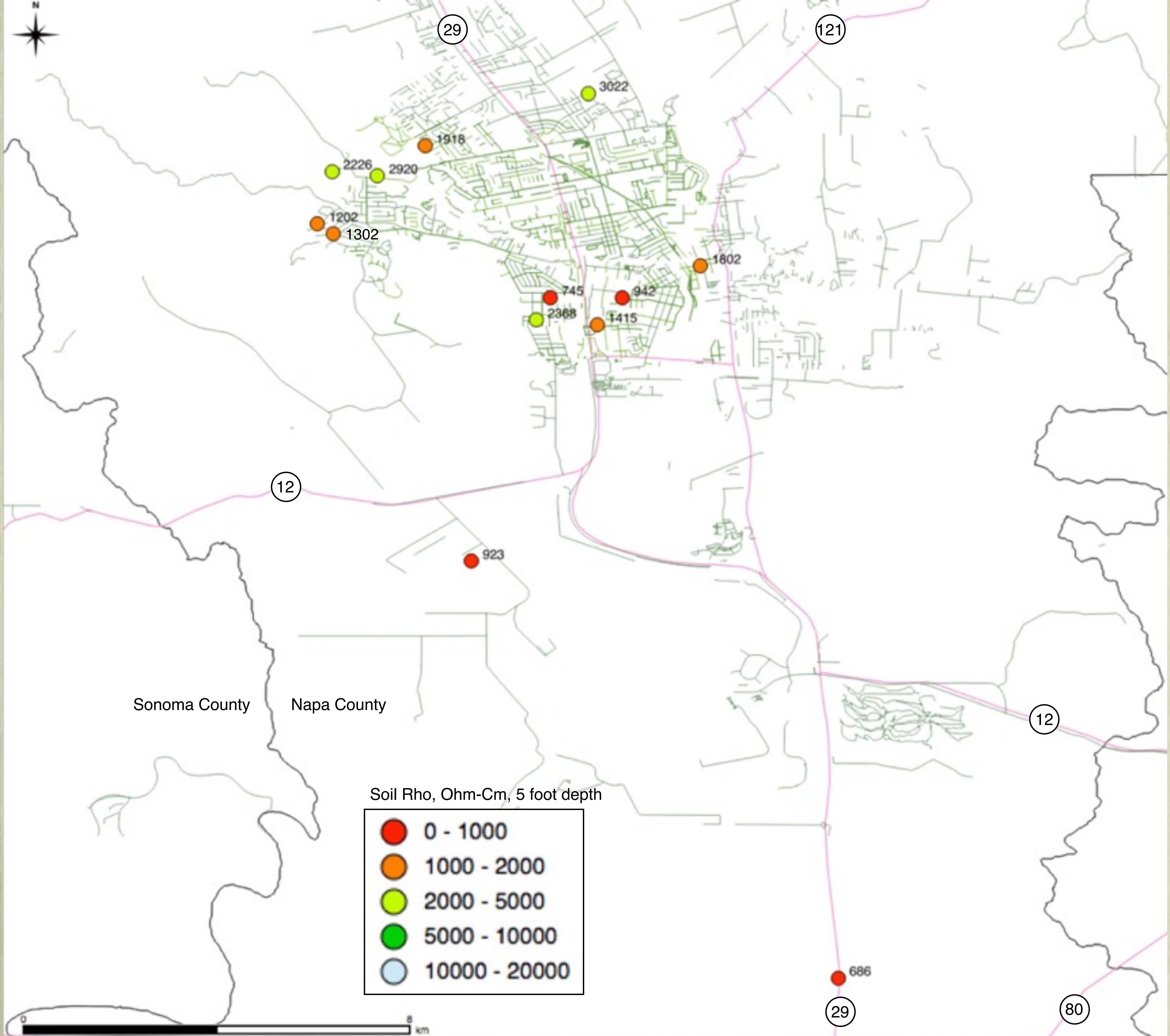
30 to 40 cm/sec

20 to 30 cm/sec

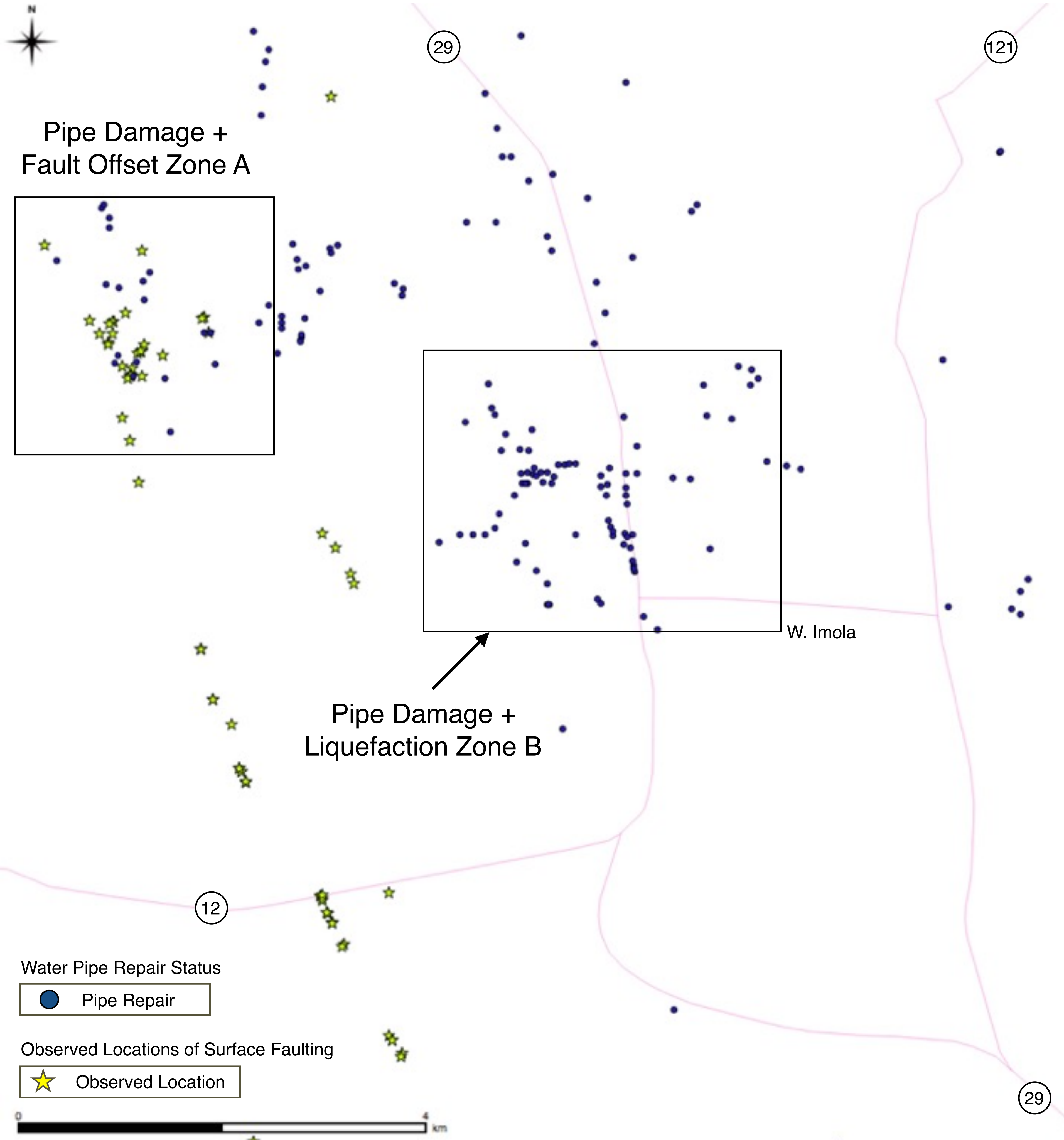
10 to 20 cm/sec

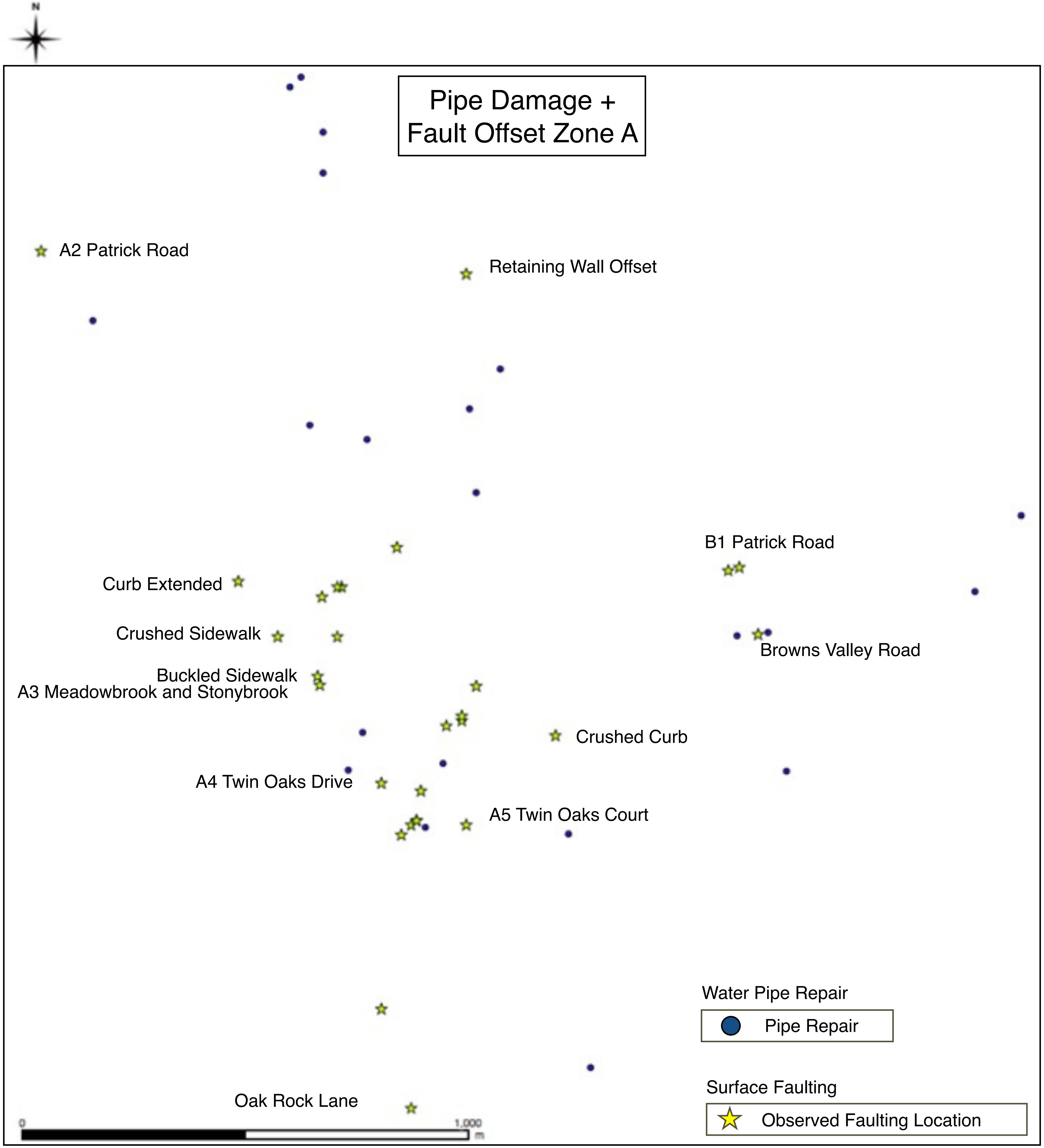
ShakeMap
Level of Shaking

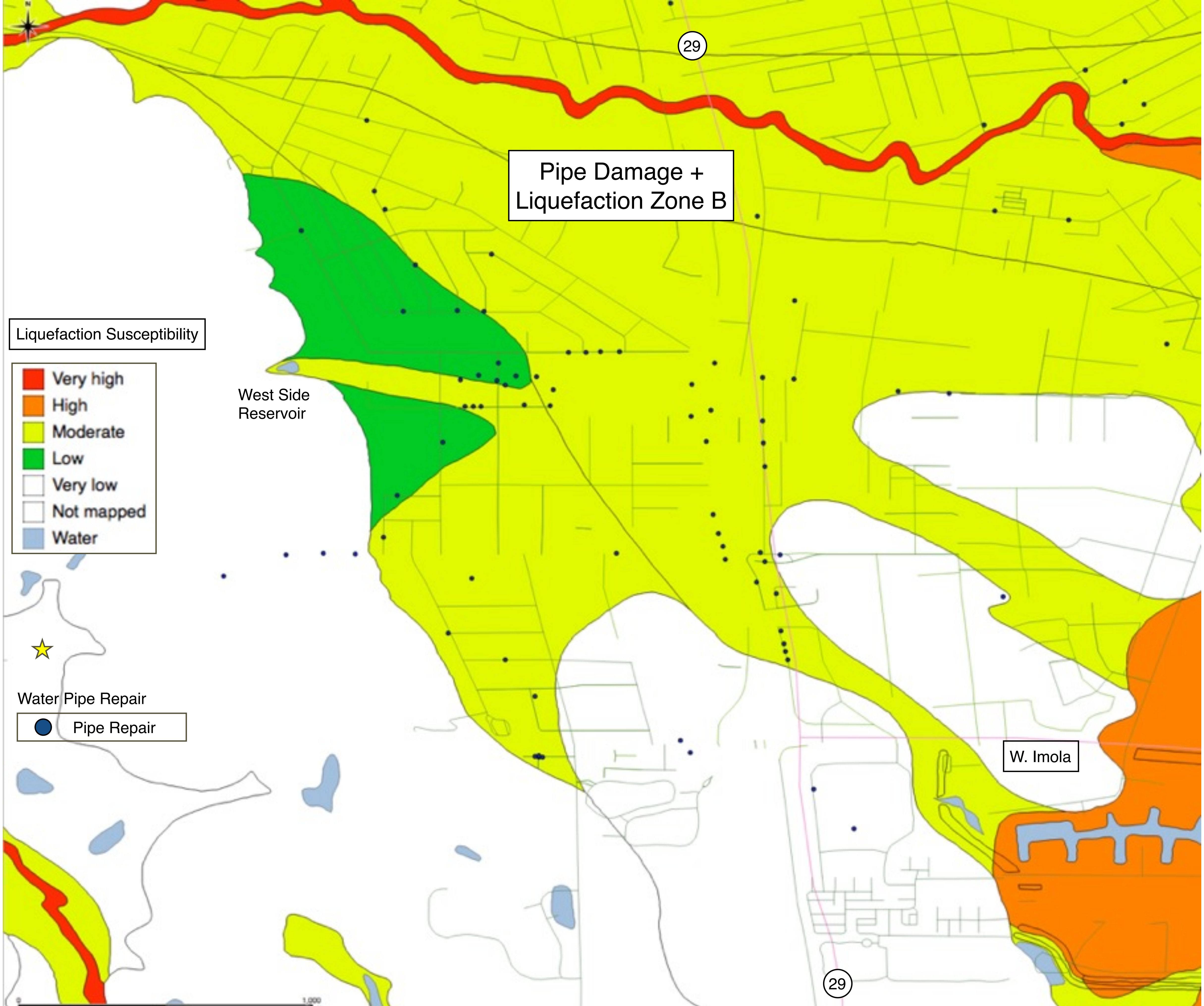


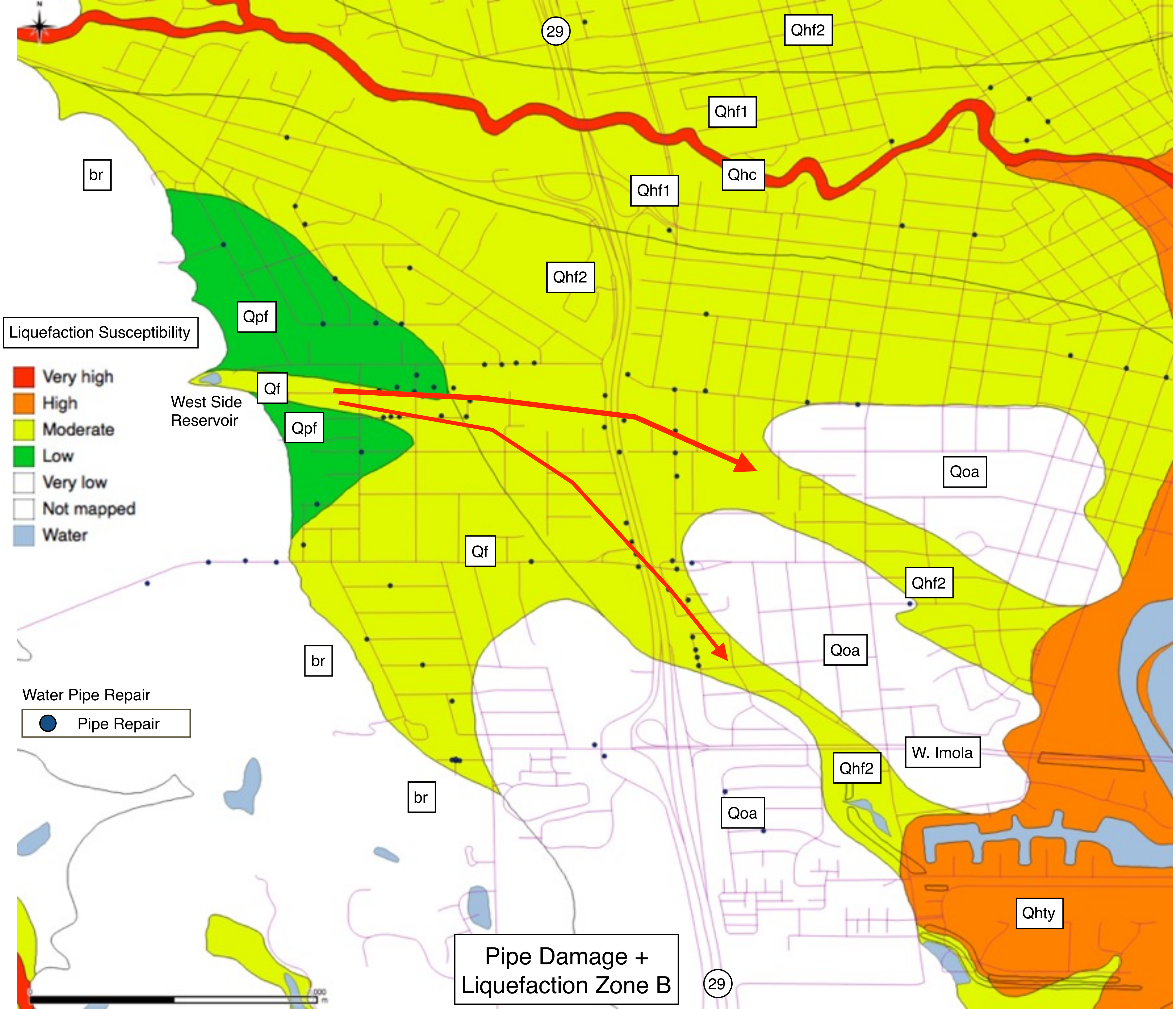


N
29
121
3022
1918
2226
2920
1202
1302
1802
745
942
2368
1415
12
923
Sonoma County
Napa County
12
Soil Rho, Ohm-Cm, 5 foot depth
0 - 1000
1000 - 2000
2000 - 5000
5000 - 10000
10000 - 20000
686
29
80
0
8
km

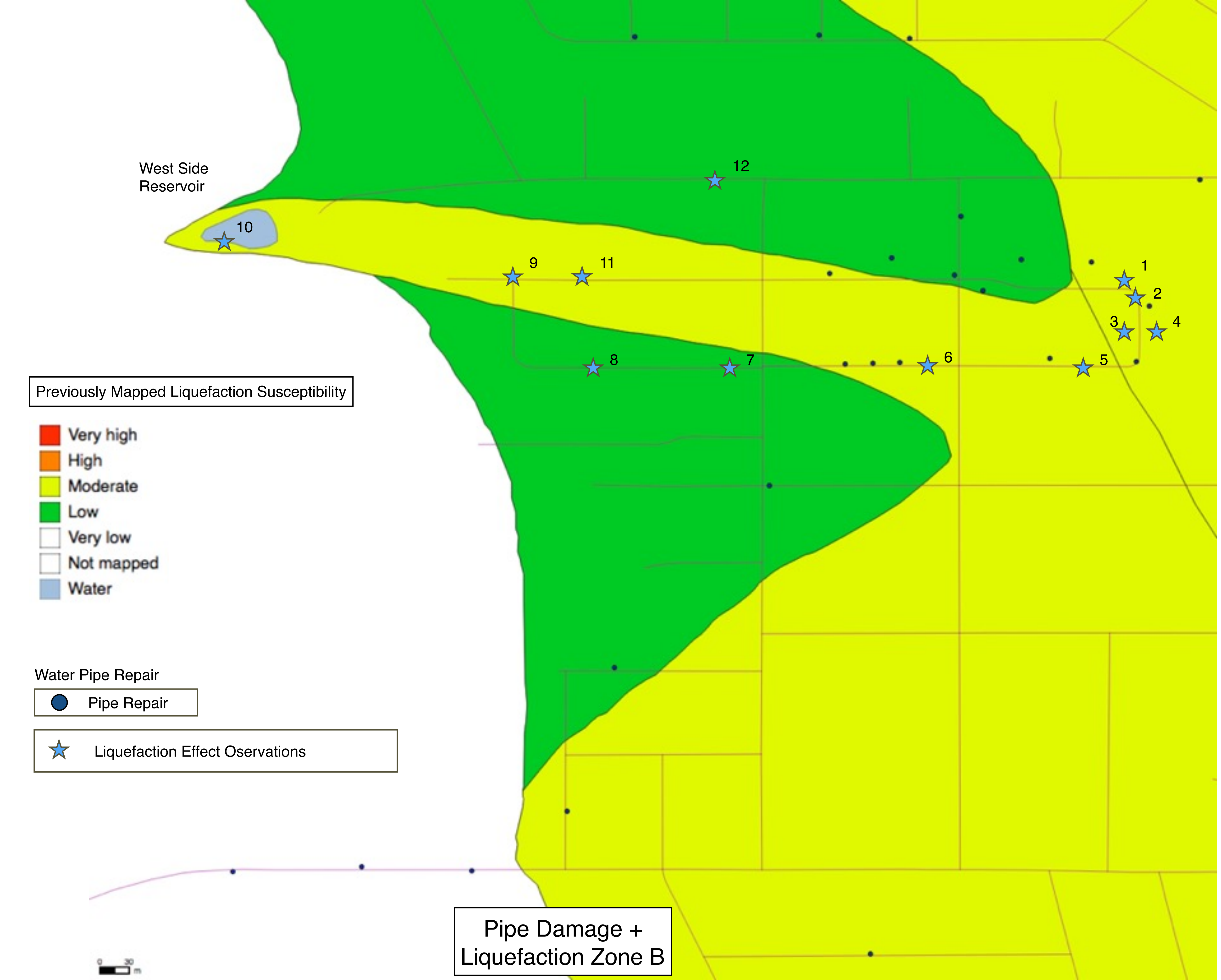

N
29
121
Pipe Damage +
Fault Offset Zone A
W. Imola
Pipe Damage +
Liquefaction Zone B
12
29
Water Pipe Repair Status
Pipe Repair
Observed Locations of Surface Faulting
Observed Location
0
4
km


N
Pipe Damage +
Fault Offset Zone A
A2 Patrick Road
Retaining Wall Offset
B1 Patrick Road
Curb Extended
Crushed Sidewalk
Browns Valley Road
Buckled Sidewalk
A3 Meadowbrook and Stonybrook
Crushed Curb
A4 Twin Oaks Drive
A5 Twin Oaks Court
Water Pipe Repair
Pipe Repair
Surface Faulting
Oak Rock Lane
Observed Faulting Location
0
1,000
m


Pipe Damage +
Liquefaction Zone B
29
Liquefaction Susceptibility
Very high
High
Moderate
Low
Very low
Not mapped
Water
West Side
Reservoir
Water Pipe Repair
Pipe Repair
W. Imola
29



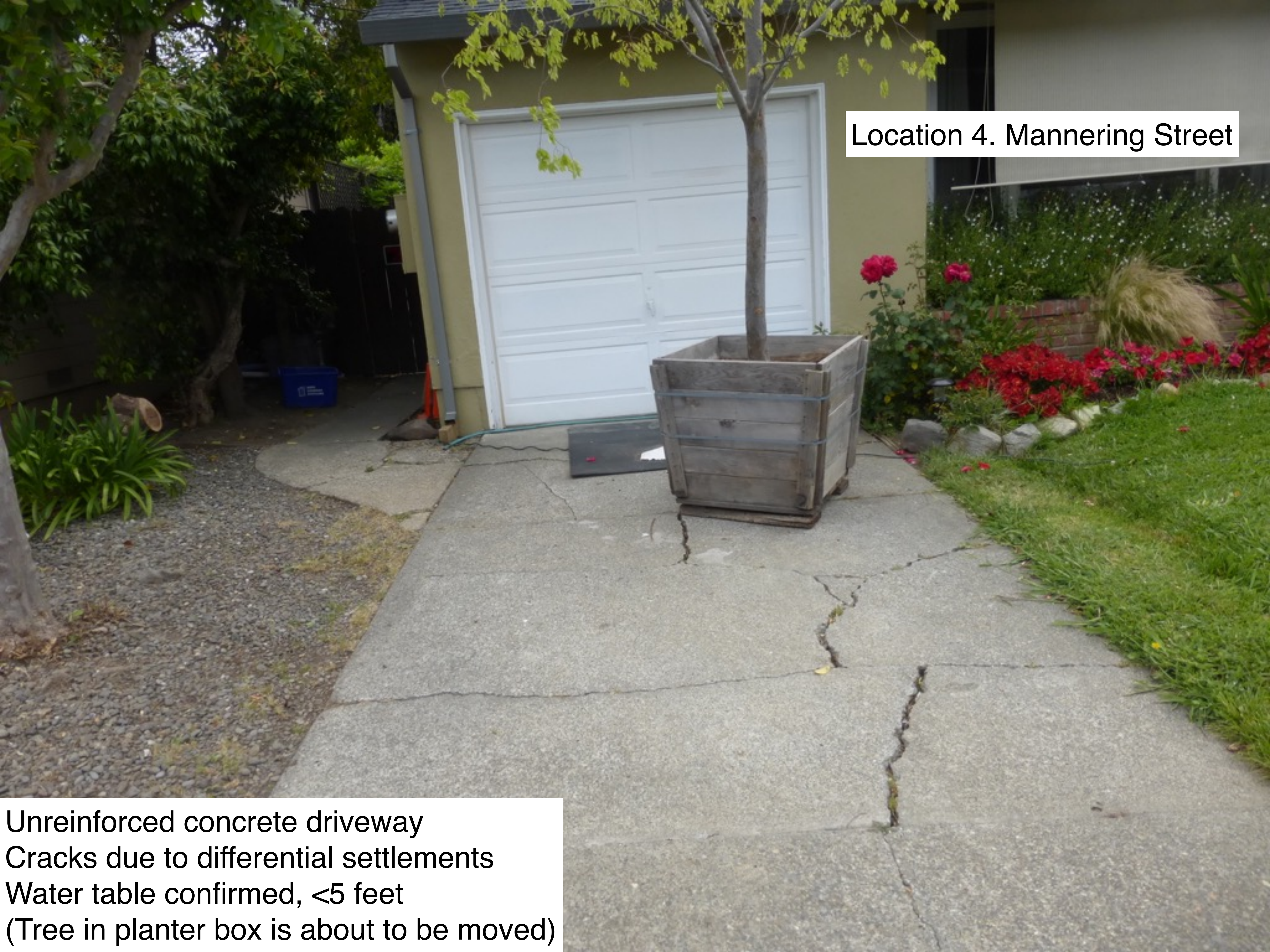
Pipe Damage + Liquefaction Zone B


West Side
Reservoir
1
2
3
4
5
6
7
8
9
10
11
12
Previously Mapped Liquefaction Susceptibility
Very high
High
Moderate
Low
Very low
Not mapped
Water
Water Pipe Repair
Pipe Repair
Liquefaction Effect Oservations
Pipe Damage +
Liquefaction Zone B


Location 1. Hilltop Drive
Residential Construction
1950s Vintage
Road Entirely Resurfaced After September 2014
Pipe Repair Post October 2014

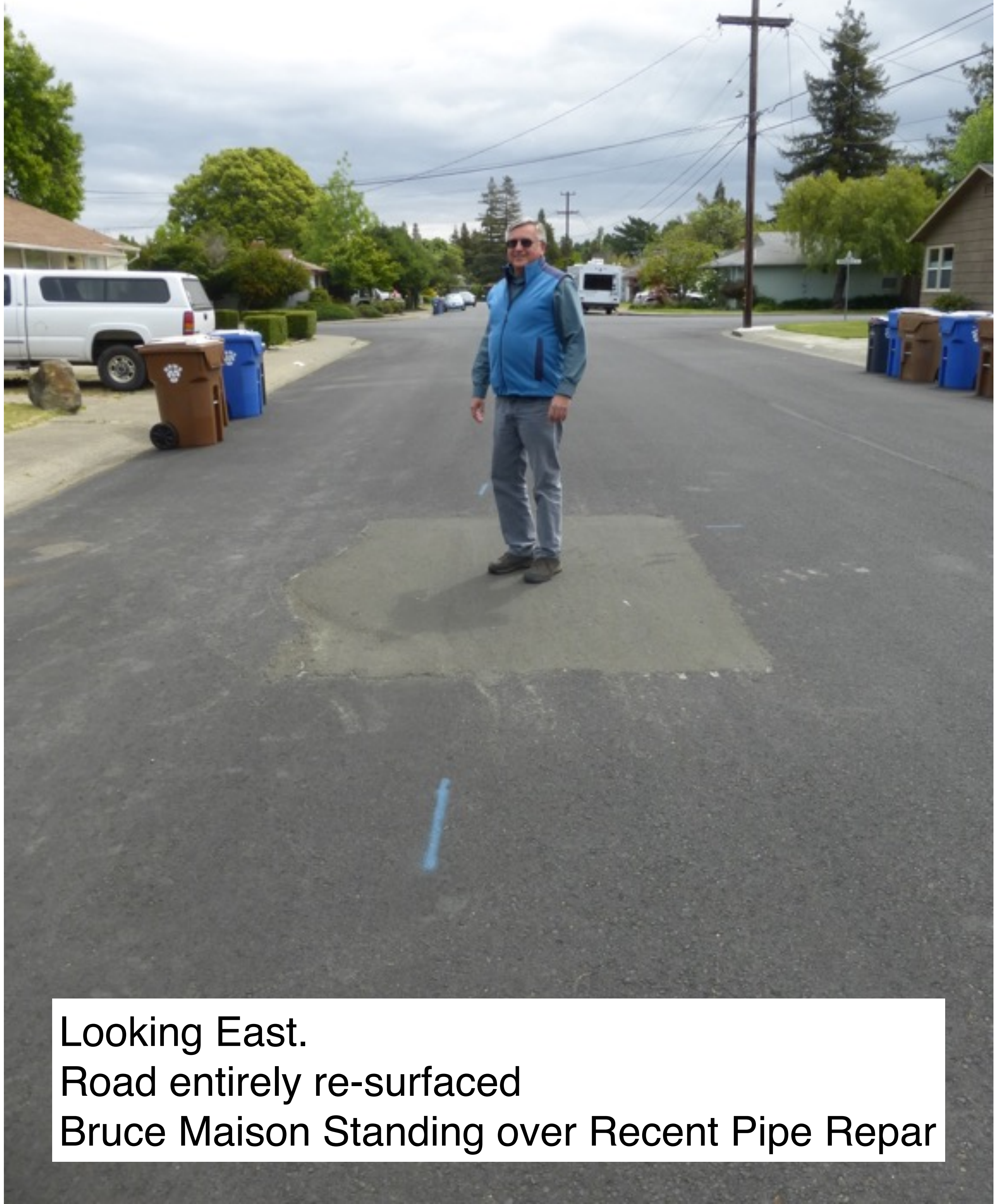

Location 2. Mannering Street
Residential Construction
1950s Vintage
Road Entirely Resurfaced After September 2014
Pipe Repairs Post October 2014


Location 3. Mannering Street
Unreinforced concrete patio
Cracks due to differential settlements


Location 4. Mannering Street
Unreinforced concrete driveway
Cracks due to differential settlements
Water table confirmed, <5 feet
(Tree in planter box is about to be moved)


Location 5. Cypress Street
Looking West.
Road entirely re-surfaced

Location 6. Cypress Street



Looking East.
Road entirely re-surfaced
Bruce Maison Standing over Recent Pipe Repar


Location 7. Cypress Street
Looking South


Location 8. Cypress Street
2956
Looking South

Location 9. Hilltop at DeVita Street


Location 10. West Side Reservoir
Looking North

PGV

	20-30 cm/sec	30-40 cm/sec	40-50 cm/sec	50-60 cm/sec	60-70 cm/sec	70-80 cm/sec	80-90 cm/sec	Total
AC					2	2	3	7
CI	3		2	16	38	41	10	110
DI				2	4	4	7	17
PVC					2			2
STL					1	1		2
UNK	3	1	2	1	9	7	2	25
Total	7	1	4	19	56	55	22	164

Pipe Repairs versus level of PGV, (Through Sept 15)

Number of Pipe Repairs Versus Mapped Liquefaction Susceptibility

	Very Low	Low	Low-Moderate	Moderate	None	Total
AC			1	5	1	7
CI	0	11	28	48	23	110
DI	2	1	4	6	4	17
PVC	1				1	2
STL				1	1	2
UNK	1	1	1	3	19	25
Total	5	13	34	63	49	164

But, some of the pipes in the yellow (moderate) boxes in fact had fairly widespread liquefaction.
Field work showed: widespread soil movements (typically 1 inch or so) and very high surface water table in soils deposited in a drainage area. This area was incorrectly mapped in USGS with a low ground water table (>10 feet), but infact has a ground water table < 5 feet from the surface.

Breakdown of actual pipe damage in Napa Earthquake

Pipe Type	Length, System-wide (miles)	Repairs due to Shaking (PGV)	Repairs due to Liquefaction (PGD)	Repairs due to Surface Faulting (PGD)	Total Repairs, August 24 to Sept 15 2014
AC	34.34	2	0	5	7
CI	149.34	86	19	5	110
DI	115.23	8	4	5	17
PVC	5.85	2	0	0	2
STL	30.38	2	0	0	2
RCCP	1.88	0	0	0	0
UNK		22	0	3	25
Total	337.01	122	23	18	163

ALA (2001) Models

$RR = k1 * 0.00187 * PGV$ (shaking)

$RR = k2 * 1.06 * PGD^{0.319}$ (liquefaction, landslide)

RR = Repair Rate per 1,000 feet (highest of two calculations)
PGV = Peak Ground Velocity (inches per second)
PGD = Permanent Ground Deformation (inches)

Updated (2015) Models

$$RR = k1 * k2 * k3 * 0.00187 * PGV$$ (shaking)

$$RR = k1 * k2 * k3 * 1.06 * PGD^{0.319}$$ (liquefaction, landslide)

RR = Repair Rate per 1,000 feet (highest of two calculations)
PGV = Peak Ground Velocity (inches per second)
PGD = Permanent Ground Deformation (inches)

Comparison, Updated (2015) and ALA (2001) Models

PGV

Pipe Type	k1 corrosion	k2 diameter	k3 material	k1 ALA 2001
	Updated 2015	*Updated 2015*	*Updated 2015*	*ALA 2001*
AC	1.0	1.0	0.3	0.5
CI assume Rho = 1000, age = 1930	2.5	1.0	1.0	1.0
DI assume Rho = 2000, age = 1940	1.5	1.0	0.3	0.5
PVC	1.0	1.0	0.3	0.5
STL	1.0	1.0	0.7	0.7
RCCP	1.0	1.0	0.2	0.2

Metal Pipes. Rho < 1500 ohm-cm. Age < 1920. k1 = 3.0. Post 1960. k1 = 1.0. 1920-1960 interpolate

Metal Pipes. Rho 1500 to 2500 ohm-cm. Age < 1920. k1 = 2.0. Post 1960. k1 = 1.0. 1920-1960 interpolate

Metal Pipes. Rho > 2500 ohm-cm. k1 = 1.0

PGD

Pipe Type	k1 corrosion	k2 Diameter (≤ 12 inches)	k3 material	k1 ALA 2001
AC	1.0	1.0	0.8	0.8
CI	1.0 (0.8)	1.0	1.0	1.0
DI	1.0 (0.8)	1.0	0.5	0.5
PVC	1.0	1.0	0.8	0.8
STL	1.0 (0.8)	1.0	0.7	0.7
RCCP	1.0	1.0	0.7	0.7

Metal Pipes. Rho < 1500 ohm-cm. k1 = 1.0

Metal Pipes. Rho > 1500 ohm-cm. k1 = 0.8

All pipe types on this page have push-on / cemented joints, unrestrained.
CI, DI pipes have no special corrosion protection.
No pipes use GENEX or similar.

Breakdown of pipe damage in Napa Earthquake due to Shaking (no liquefaction, no surface faulting)

Pipe Type	Length, System-wide (miles)	Actual Repairs due to Shaking	Forecast Repairs due to Shaking
AC	34.34	2	2.4
CI	149.34	86	88.5
DI	115.23	8	12.3
PVC	5.85	2	0.4
STL	30.38	2	5.0
RCCP	1.88	0	0.1
UNK		22	
Total	337.01	122	108.8

With Updated Seismic Models

Breakdown of pipe damage in Napa Earthquake due to Liquefaction

Pipe Type	Length, System-wide (miles)	Actual Repairs due to Liquefaction	Forecast Repairs due to Liquefaction
AC	34.34		
CI	149.34	19	21.2
DI	115.23	4	4.3
PVC	5.85		
STL	30.38		
RCCP	1.88		
UNK		0	
Total	337.01	23	25.5

With Updated Seismic Models

Pipe Fragility Models - Lessons Learned from Napa

- The updated (2015) pipe fragility models provide very good forecasts of the pipe damage.
  - Napa has VERY corrosive soils. This explains some of the high failure rates seen in August 2014.
  - Napa did have Liquefaction. This explains some of the high failure rates.
  - Damage of water pipes due to surface faulting (<15 cm) was modest.

Pipe Fragility Models - Lessons Learned from Napa

- Gas pipelines had ZERO pipe failures in this earthquake. Water pipes had 164 failures.
- Gas pipelines used either heavy wall welded steel pipes (transmission) or MDPE pipes (distribution).
- ZERO Pipe failures (gas) versus 164 pipe failures (water), for pipes exposed to the same PGV and PGD.
- Aggressive soils (Rho < 1,500 ohm-cm) explains a LOT of the cast iron and ductile iron (without special corrosion protection) water pipe failures.

Questions?