4 EFFECTS OF SURFACE FAULT RUPTURE ON INFRASTRUCTURE

4.1 Introduction

The preliminary reconnaissance efforts performed by GEER on August 24, 2014 (the day of the M6 South Napa earthquake) noted significant damage to infrastructure due to ground rupture in the areas northwest of the earthquake epicenter. While infrastructural damage in lightly populated areas was limited to roadways, boundary barriers or isolated structures, damage in heavily populated areas was extensive. The West Napa residential neighborhoods in the vicinity of Browns Valley Road and Buhman Avenue, herein referred to as the Browns Valley area (BVA), were observed to have been particularly affected by ground rupturing and intense seismic shaking. Located approximately 10 km north of the epicenter, the BVA experienced what was suspected to be surface fault rupture from Oak Rock Ln (southern end of this segment) to Redwood Rd (northern end), and west of Browns Valley Rd. and Buhman Rd. Although many residents in close proximity of the fault experienced significant damage to personal property from intense ground shaking, most of the structural damage was observed in conjunction with surface fault rupture. This section summarizes the GEER effort to document the effects of surface fault rupture on infrastructure in the BVA. Appendix C of this report contains all supporting documents upon which our observations have been drawn.

4.2 Reconnaissance and Data Collection

4.2.1 Investigation area

From August 25 through August 28, 2014, several teams collected measurements and observations throughout the Browns Valley area in the form of detailed maps of damage to individual properties. A total of 39 structures were summarily observed, of which 27 were carefully mapped with the consent of each owner. In each case, damaged properties coincided with the north trending trace of the surface rupture. Figure 4.1 illustrates the locations of mapped properties and surface fault rupture. For reference, each property has been numbered according to decreasing latitude and preceded by “H” (i.e., H39), as shown in the table of contents of Appendix C.

A second area, also exhibited significant infrastructure damage due to surface fault rupture. Herein referred to as BVA 2, this area is bounded approximately by Browns Valley Rd. to the west and south, Redwood Rd. to the north and Westview Dr. to the east. Due to time constraints, BVA 2 was visited during the afternoon of August 28 though not mapped to the same extent as the afore mentioned properties. A simplified map of the damage observed in BVA 2 is presented in the upper right corner of Figure 4.1.

4.2.2 Structures

Structures in the Browns Valley area consist of primarily single-family residences and associated structures such as swimming pools, detached garages, guest houses, tool sheds, and various forms of hardscape. Due to the extensive and persistent damage in this area, the BVA residential properties were made the primary focus for evaluating the effects of surface fault rupture on infrastructure after the M6 South Napa earthquake.

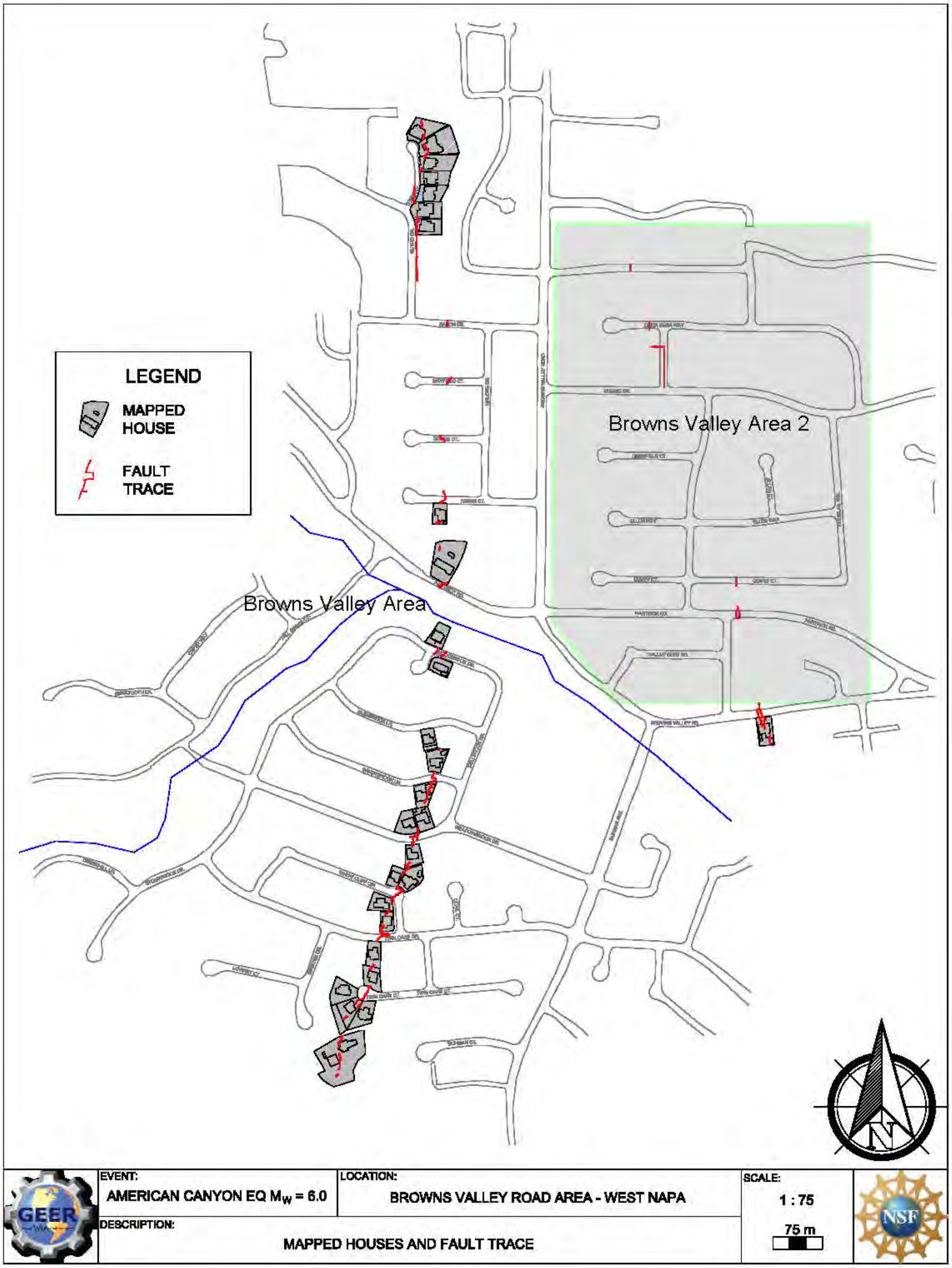


Figure 4.1 Location of mapped properties and surface fault rupture in the Browns Valley area. [NSF-GEER; J. Cohen-Waeber, R. Luque, R. Lanzafame, N. Wagner; 09/12/2014]

Residences typically consisted of single-story wood-frame structures with attached garages. A majority of the inspected structures south of Karen Dr. were founded on reinforced concrete perimeter strip footings with spread footing-supported wooden floor beams or reinforced concrete slab-on-grade. The inspected structures north of Karen Dr. were founded on reinforced concrete grade beams and 2-m to 4-m-deep reinforced concrete piers.

In addition to the physical residence, measurements were made on associated structures, including:

- Detached garages,
- Asphalt pavement,
- Concrete driveway slabs (reinforced and unreinforced),
- Concrete patios, curbs, gutters, sidewalks and driveway bibs (reinforced and unreinforced),
- Retaining walls and fences,
- Light structures (i.e., aluminum sheds with block foundations, wood trellis).

When possible, the property owners were interviewed to confirm if the damage observed was in fact associated with the August 24, 2014 M6 South Napa earthquake.

4.2.3 Methodology

Upon identifying a residence for mapping and obtaining permission from the property owner, a walk-through was conducted to observe seismic damage, after which a detailed map was developed. Only damage of clear seismic origin was mapped, including concrete and ground surface cracking, horizontal and vertical displacement of structures, and rotation of structures. Each damage feature was measured and photographed while an approximately scaled schematic representation of each feature was prepared. Specific measurements as reported in this section regularly included:

- Horizontal and vertical offset of new cracks
- Vertical depth of ground surface and structural cracks
- Displacement of structures away from adjacent ground
- Lengths of sidewalk sections before and after buckling
- Horizontal and vertical displacement of residence walls relative to foundations

In some cases structures showed apparent compression, either through buckling of stiff materials or by apparent strain relative to the adjacent ground surface (e.g., bulging of grass over concrete). Whereas pre-buckling dimensions of stiff structures such as sidewalks are typically possible to measure, some compressional features were not measurable.

Architectural damage was generally noted though not carefully measured or mapped. While drywall, stucco and paint cracks were prevalent as a result of minor structural deformation, these were recorded only to describe a specific structural failure mechanism or lack thereof. For example, radial floor cracks at H37 illustrate settlement of the foundation or door and window frame cracks at H31 illustrate the sense of movement within the structure. In the case of H13 however, the minor architectural damage observed was evidence of a successful seismic retrofit. Detailed maps for H13 and H37 are presented in Appendix C.

Residences in the BVA 2 (Figure 4.2) were not mapped individually. Due to time constraints, mapping

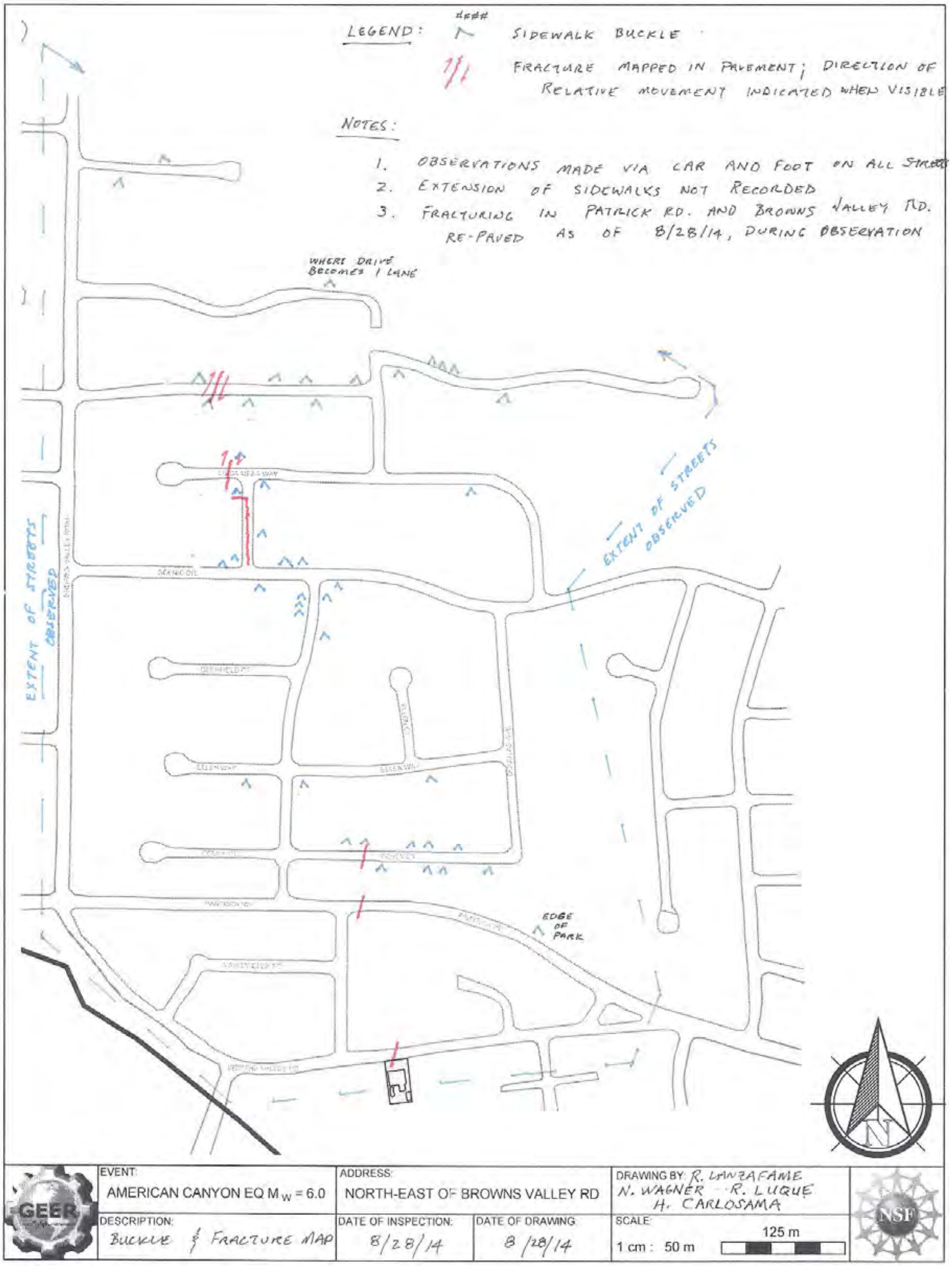


Figure 4.2 Map of surficial damage in the Browns Valley Area 2, Northeast of Browns Valley. [NSF-GEER; H. Carlosama, R. Luque, R. Lanzafame, N. Wagner; 09/12/2014]

was conducted on foot along roads and sidewalks and consisted of locating the general characteristics of ruptured asphalt pavement and buckled sidewalks. Asphalt cracking was drawn at approximate scale and the residential properties that were entered were identified. In some cases the asphalt pavement had already been repaired by the date of the reconnaissance.

4.3 Types of Damage

The damage typically observed during our field reconnaissance can generally be divided into the following three categories:

- Cracking of reinforced concrete and concrete masonry components within structures.
- Displacement between structures and adjacent ground or structures.
- Cracking of paved and unpaved areas at the ground level.

Though secondary to the scope of this investigation, additional recorded damage included: rupture of asphalt pavement, architectural damage, and failed chimneys.

Cracking of reinforced concrete and concrete masonry structures ranged from cosmetic cracking of swimming pool patios to cracking of building foundations. Table 4.1 summarizes and describes the different modes of concrete and masonry damage observed.

Where damage due to the displacement of structures with respect to adjacent ground or structures occurred, architectural damage was also prevalent. Generally, the most significant structural damage observed from displacement was horizontal and vertical offset of residence walls from the underlying foundations. Table 4.2 summarizes and describes the different modes of damage observed in relation to displacement across or between structural elements.

Damage due to ground cracking in paved and unpaved areas serves as a clear indication of the fault trace. Thus fracturing of asphalt pavement and unpaved ground surfaces were mapped in streets and residential properties where observed. These observations will be important for a better understanding of infrastructural behavior in the surface fault rupture area. Ruptures occurred with various degrees of severity from thin fissures to deep open cracks to buckled asphalt and soil mounds. While ruptures in unpaved surfaces (i.e., grass or dirt surfaces) did not exhibit as dramatic an appearance as those in asphalt, all fractures typically had distinct geometries which describe the sense of movement along the fault. Table 4.3 summarizes and describes the different modes of ground cracking observed during our reconnaissance.

Cracking of window and door frames in residences was common and generally consisted of hairline cracking in the wall façade, extending diagonally from the corners. Several toppled chimneys were also observed in the reconnaissance area. These failures typically occurred where unreinforced and unbraced brick chimneys extended above a structure roof more than approximately 0.5 m to 1 m. Although window and door frame cracking and chimney toppling were widely observed, their occurrence is typically not directly due to surface fault rupture; therefore, these observations are generally not uniformly included in the residential house mapping results.

Table 4.1 Observed types of reinforced concrete and concrete masonry structural cracking.

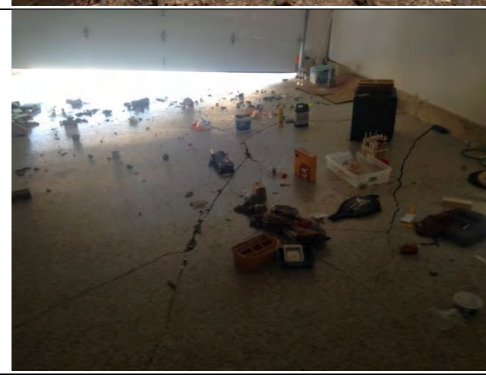
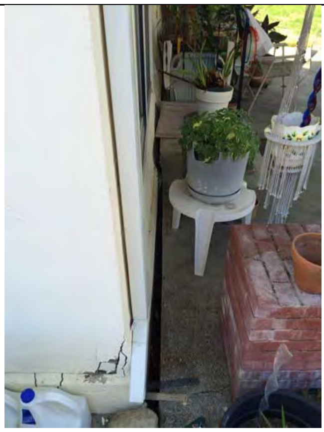
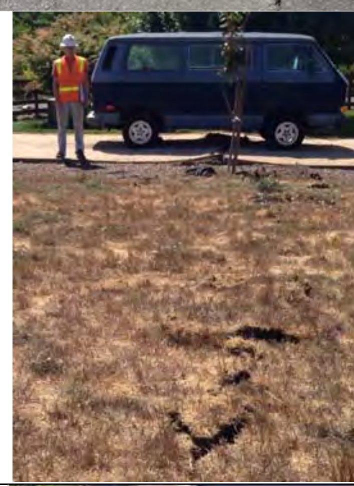
Cracking of concrete and masonry structures	
Foundations Primarily consisted of cracking of reinforced concrete strip footings or grade beams; visible from outside residence or within crawlspace. Photo reference: [NSF-GEER; N 38.3040 W 122.3430; 08/25/14 13:47]	
Concrete (non-foundation) Typically consisted of new fractures within garage concrete slabs, driveways, patio slabs, planter edges and other concrete structures, which were sometimes reinforced. Photo reference: [NSF-GEER; N 38.3024 W 122.3436; 08/27/14 11:33]	
Sidewalk/curb buckling Buckling of sidewalks, curbs or other linear concrete structures due to compressive forces during fault rupture displacement or seismic shaking. Photo reference: [NSF-GEER; N 38.3018 W 122.3439; 08/25/14 10:38]	

Table 4.2 Observed types of displacement between structures and adjacent ground or other structures.

Displacement between structures and adjacent ground or other structures	
Structure / Ground Displacement of structure relative to ground that had been immediately adjacent prior to the seismic event. Photo reference: [NSF-GEER; N 38.3042 W 122.3429; 08/25/14 13:56]	
Structure / Structure Displacement of structure relative to another structure that had been immediately adjacent prior to the seismic event. Photo reference: [NSF-GEER; N 38.3041 W 122.3429; 08/25/14 13:18]	
House frame on foundation Displacement of superstructure relative to its foundation in the horizontal or vertical direction. Photo reference: [NSF-GEER; N 38.3027 W 122.3436; 08/25/14 10:11]	

Displacement between structures and adjacent ground or other structures (Continued)	
Settlement Detached garage on strip footings and slab-on-grade. Structure settled west (i.e., right) approximately 5 cm due to surface fault rupture along edge of footing. Photo reference: [NSF-GEER; N 38.3052 W 122.3369; 08/28/14 10:00]	
Light structures Displacement of light structures was measured where evidence of movement provided confirmation of displacement length. Photo reference: [NSF-GEER; N 38.3042 W 122.3429; 08/25/14 14:18]	
Retaining walls Separation of masonry blocks due to surface displacement in 1.5 - m tall landscape retaining wall. Photo reference: [NSF-GEER; N 38.3128 W 122.3429; 08/28/14 16:32]	
Compression of fences Fences were compressed in several cases; in one case a local strain measurement was obtained by measuring before and after length. Photo reference: [NSF-GEER; N 38.3015 W 122.3440; 08/25/14 10:55]	

Table 4.3 Observed types of ground rupture.

Ground Rupture	
Compression in paved areas Asphalt buckling from end [NSF-GEER; N 38.3038 W 122.3430; 08/25/14 10:24]	
Extension in paved areas Asphalt fracture away from compressed area shown above [NSF-GEER; N 38.3017 W 122.3440; 08/25/14 13:20]	
Compression in unpaved areas Soil mound from ground cracking [NSF-GEER; N 38.2980 W 122.3446; 08/26/14 12:25]	
Extension in unpaved areas Ground surface rupture in side-yard [NSF-GEER; N 38.3045 W 122.3427; 08/25/14 15:24]	

4.4 Structural Performance Mapping

Illustrated in Figures 4.3 and 4.4 are the detailed structural performance maps for properties H01 and H21 (respectively). These cases demonstrate the performance of properties on pier and grade beam foundations (H01) and strip footings (H21), when directly affected by surface fault rupture.

In the case of H01, the site's geotechnical consultant allowed access to the property where surface rupture was observed to cross through the NE corner of the residence. Surface rupture was observed from a buckle in the wooden fence along the property's southern boundary, northward through displaced hardscape and under the structure. The rupture surface re-appeared along the north end of the residence from beneath the structure as a 3 cm open soil fissure with approximately 1 cm of right lateral displacement. Up to 5 cm of displacement was observed in the NE corner of the structure from gaps between the perimeter foundation and surrounding landscape. Damage to the northern external façade of the structure included approximately 0.5 cm cracks extending from the corners of the door frame, a roof beam apparently detached from the structure's wall, and a cracked foundation (approximately 0.5 cm). The consultant also reported damage to the floor boards within the structure which could be seen from the exterior though access to the structure was not possible to determine the cause.

In a similar fashion to H01, the residence at H21 experienced significant damage due to the surface rupture progressing directly through the structure. Along the southeast end of the property, an open fissure 8 cm wide and up to 70 cm deep cut adjacent to the West wall of a detached garage, causing the slab-on-grade building to tilt slightly to the West. The rupture was further pronounced to the North in the building crawl space by large open soil fissures. A 3 cm wide crack and several small gaps within the northern most perimeter strip footing were clearly a result of the ground rupture, also causing the structure's cripple wall to rack approximately 7 degrees to the East. North of the residence, the surface rupture was further pronounced through the paved driveway. Additionally, both wooden fences along the southern and northern property boundaries were buckled, with displaced fence posts up to 16 and 21 cm, respectively.

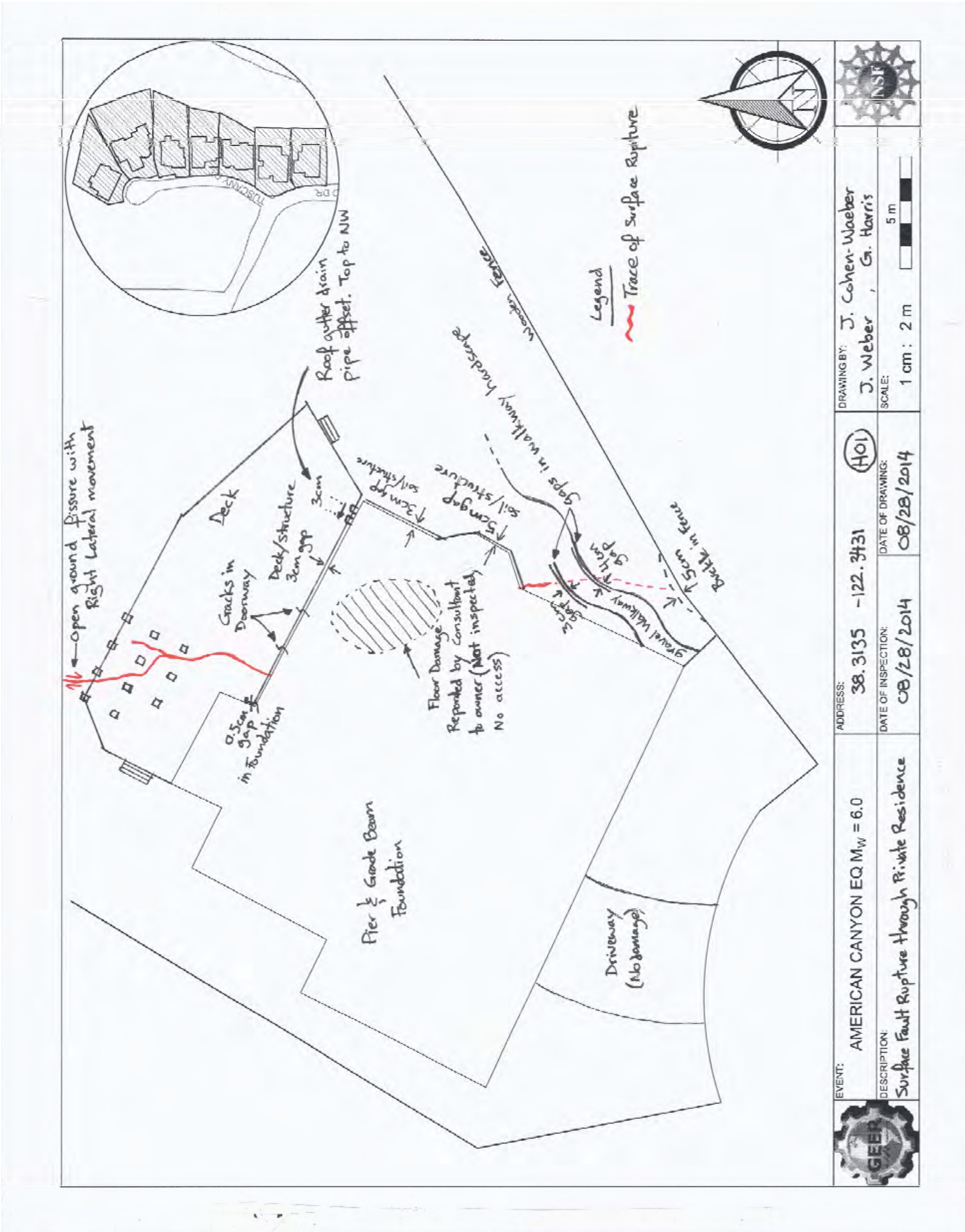


Figure 4.3 Map of Structural Performance, Northwest Browns Valley.
[NSF-GEER; J.Cohen-Waeber, J. Weber, G. Harris; 08/28/2014]

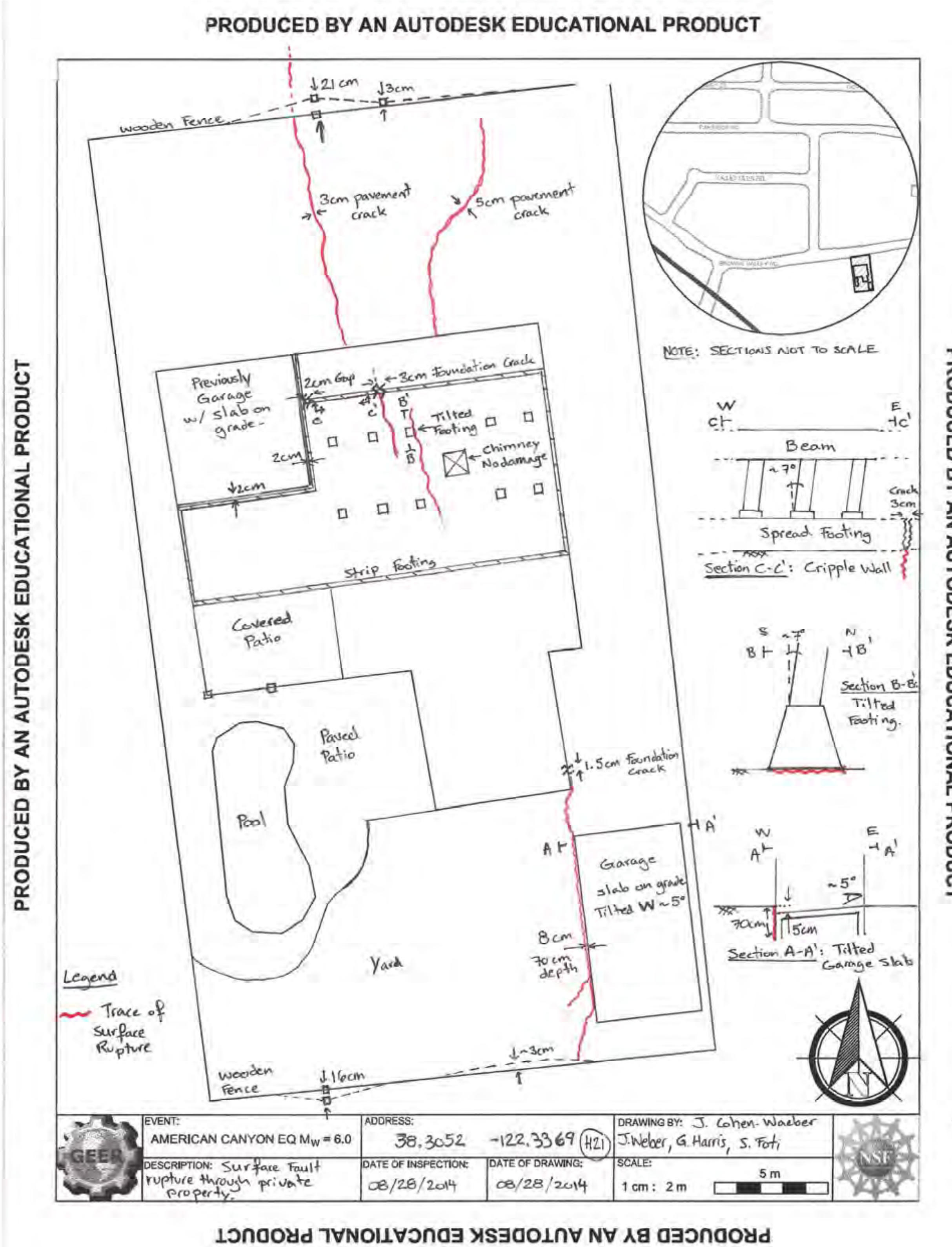


Figure 4.3 Map of Structural Performance, Northwest Browns Valley. [NSF-GEER; J.Cohen-Waeber, J. Weber, G. Harris; 08/28/2014]

4.5 Summary of Structural Damage

Tables 4.4 through 4.6 summarize our observations on damage to infrastructure due to surface fault rupture. Table 4.4 describes the location for each of the observed structures in the Browns Valley area, as well as the foundation type for mapped properties. Tables 4.5 and 4.6 summarize the various types and damage observed at each site, including quantitative measurements when available. The complete observations have been included as Appendix C of this report, in the form of detailed maps and selected photos. For reference, each property has been numbered according to decreasing latitude.

Table 4.4 Summary of mapped and observed properties in the Browns Valley area.

House No.	Lat. (°N)	Long. (°W)	Foundation Type (if mapped)	House No.	Lat. (°N)	Long. (°W)	Foundation Type (if mapped)
1	38.3135	122.3431	Piers and Grade Beams	21	38.3052	122.3369	Strip Footing / Slab
2	38.3133	122.3431	Piers and Grade Beams	22	38.3048	122.3427	Strip Footing
3	38.3131	122.3431	Piers and Grade Beams	23	38.3045	122.3429	Strip Footing
4	38.3128	122.3431	Piers and Grade Beams	24	38.3041	122.3429	Strip Footing
5	38.3126	122.3431	Piers and Grade Beams	25	38.304	122.3432	Strip Footing
6	38.3124	122.3432	Piers and Grade Beams	26	38.3037	122.3434	Not Mapped
7	38.3122	122.3432	Piers and Grade Beams	27	38.3036	122.3432	Strip Footing
8	38.3102	122.3426	Not Mapped	28	38.3033	122.3434	Strip Footing
9	38.3098	122.3426	Not Mapped	29	38.3032	122.3432	Strip Footing
10	38.3075	122.3426	Not Mapped	30	38.3029	122.3435	Strip Footing
11	38.3095	122.3428	Not Mapped	31	38.3027	122.3436	Strip Footing
12	38.309	122.3426	Not Mapped	32	38.3022	122.3438	Piers and Grade Beams
13	38.3087	122.3427	Not Mapped	33	38.3019	122.3439	Strip Footing
14	38.3082	122.3427	Strip Footing / Slab	34	38.3017	122.3443	Strip Footing
15	38.3076	122.3425	Strip Footing	35	38.3015	122.3442	Strip Footing
16	38.3066	122.3427	Strip Footing	36	38.3015	122.344	Strip Footing
17	38.3061	122.3427	Strip Footing	37	38.3011	122.3442	Strip Footing / Slab
18	38.3056	122.3423	Not Mapped	38	38.2981	122.3442	Not Mapped
19	38.3055	122.3432	Not Mapped	39	38.2967	122.3439	Not Mapped
20	38.3052	122.3429	Not Mapped				

Table 4-5 (Page 1 of 2) – Summary of Damage of Mapped Residences

House No.	Overall Level of Damage	Cracking of concrete and masonry structures: Foundations	Concrete (non-foundation)	Sidewalk/gutter buckling	Displacement between structures and adjacent ground or other structures: Structure / Ground	Structure / Structure	House frame on foundation	Settlement	Light structures	Retaining walls	Compression of fences	Ground rupture	Notes/Other
1	H	X			5				3			X	Patio detached from house, cracks in house floor, structural damage from shearing of building.
2	H	X	2	3	1	11					X	X	
3	H	X		X	5	5	11		60			X	Reinforced concrete driveway and garage slabs shifted N. Entry stair case shifted N. Front of house frame shifted N on foundation. Car in garage moved E-W.
4	H	3			2	2				3	X	3	Dry masonry wall damage
5	M	1.5				3							Damage to garage and front façade of home only.
6	M		3			2		8				5	Damage to entrance stair cases and retaining walls. Settlement of fill behind small wall.
7	M		5									X	Driveway and entry way stairs affected only.
14	L		X	X							X	X	Recently remodeled home with large moment frame parallel to fault trace
15	M	X		X	2					X		X	Principal door is not functional. Not cracks observed in the ground within the crawl space
16	M		X		5								General ground movement down-slope tilting light structures.
17	L		X		3								
20	L			X	4								
21	H	3			8 H 70 D	2	X	5	X		X	X	Garage slab tilted 5^{o} W, House shifted E on tilted cripple wall and footing (7^{o} N and E).
22	L			X		11						X	1.5 cm cracks in garage N-S walls
23	L			X	4				5	1			Extensive rupturing in gravel side-yard; shed displaced vertically due to rupture beneath.

1. Numbers represent maximum measurements in cm of the particular type of damage found for each house; H = horizontal, V = vertical, D = depth.
2. Overall Level of Damage types are: H = high, M = medium, L = low, X = observed but not measured as discussed in the text.

Table 4-5 (Page 2 of 2) – Summary of Damage of Mapped Residences

House No.	Overall Level of Damage	Cracking of concrete and masonry structures			Displacement between structures and adjacent ground or other structures								Notes/Other
		Foundations	Concrete (non-foundation)	Sidewalk/gutter buckling	Structure / Ground	Structure / Structure	House frame on foundation	Settlement	Light structures	Retaining walls	Compression of fences	Ground rupture	
24	H	0.5	5	X	10		6 H 3 V		20			X	Shed displaced horizontally on concrete slab. Significant movement of house frame on foundation and displacement between structures and ground/foundation.
25	L			X	4								Breaking/deformation of rebar in driveway/sidewalk joint; house structure undamaged.
27	H	X	X			11	13			3		X	Rupture between two retaining walls at SW property corner with no apparent damage to retaining walls. S end of house shifted W on foundation.
28 / 29	L			150 H 32 V							X		Rupture between two apparently undamaged homes.
30	L		5	X	8								Damage primarily to driveway and sidewalk.
31	H	5	8				5		5		X	X	Garage: slab apparently unreinforced, door shifted. House shifted on spread footing at NW corner.
32	H	X	2.5 H 1 D		14	10						X	Split redwood tree. Right-lateral deformations apparent throughout survey. Significant cacking in garage slab and of adjacent wall strip foundation.
33	L				5.5				27			8 H 20 D	Displaced wood trellis structure on concrete slab and rupture along backyard slope.
34	L					1.5							Cracking of concrete at edge of pool and displacements between side-drive slab.
35	M		X	X	2					1	0.003 3	5-6 V 70 D	Multiple cracks in retaining wall up to 0.8 cm. Strain due to compression along wood fence measured as ε = 0.33%.
36	M			X	3					X		13 H 76 D	Fallen statues and 23 cm diameter tree; localized comp. of wall bulged 20 cm H over 1.47 m
37	M	X	5	10 H 8 V	5 H 64 D			3			X	5	Radial cracks in bathroom due to settlement of cracked foundation

1. Numbers represent maximum measurements in cm of the particular type of damage found for each house; H = horizontal, V = vertical, D = depth.
2. Overall Level of Damage types are: H = high, M = medium, L = low, X = observed but not measured as discussed in the text.

Table 4-6 Summary of Pavement Damage.

Street	Latitude (degrees N)	Longitutde (degrees W)	Asphaltic Pavement Cracking	Asphaltic Pavement Buckling
Buhman Ct	38.3007	122.3443	5 H	8 V
Twin Oaks Dr	38.3025	122.3438	10 H	20 V
Twin Oaks Ct	38.3017	122.344	12 V 20 H 50 D	20 V
White Cliff Cir	38.3031	122.3434	5 H 16-50 V	8 V
Meadowbrook Dr	38.3038	122.3441	5 H	24 V
Sandybrook Dr	38.3046	122.3428	5 H	20 V
Browns Valley Rd	38.3055	122.3370	5 H	
Kerns Ct	38.3085	122.3427	X	
Sutro Dr	38.3123	122.3432	X	
Tuscany	38.3129	122.3432	3 H	
Westminster Way	38.3117	122.3395	X	
Linda Mesa Way	38.3109	122.3391	X	
Mason St	38.3104	122.3388	X	
Covey Ct	38.3074	122.3375	X	
Partick Rd	38.3069	122.3375	X	

1. Numbers represent maximum measurements in cm of the particular type of damage found for each house; H = horizontal, V = vertical, D = depth.
2. Overall Level of Damage types are: H = high, M = medium, L = low, X = observed but not measured, as discussed in the text.

4.6 Discussion

4.6.1 Generalized Damage Assessment

A preliminary assessment of the quantitative descriptions of damage summarized above shows certain characteristic interactions between surface fault rupture and the mapped damage of the overlying infrastructure. Based on these general observations, 13 of the 27 investigated properties showed concrete slabs cracked up to 8 cm wide. Similarly, 12 of the 27 observed cases, experienced cracking of their foundation by up to 3 cm, and 5 of these structures were shifted up to 11 cm off of their foundation.

The performance of different foundation types under similar circumstances is also a significant observation. Of the 8 investigated properties that were founded on pier and grade beam foundations, 6 had foundation damage, 4 exhibited cracks in concrete, 6 experienced displacement between the structure and ground as well as between structures and 1 experienced displacement of the structural frame from the foundation. Of the 19 investigated properties that were founded on strip footings, 6 had foundation damage, 9 exhibited cracks in concrete, 16 experienced displacement between the structure and ground as well as between structures and 4 experienced displacement of the structural frame from the foundation.

However, with the gathered information, it is not yet possible to draw conclusions on the differences in behavior between different foundation types.

4.6.2 Special Cases

There were several special cases in which atypical occurrences may warrant further investigation.

Though located several km south of the Browns Valley study area, a right-lateral offset of approximately 10 cm was observed through Los Carneros Ave. This offset occurred at the Stone Bridge School where windows were observed to have broken. Although detailed measurements of the Stone Bridge School were not collected as a part of this effort, data may have been collected by others and should be compiled. In comparison, no significant damage was observed at the Browns Valley School.

The properties located at investigation points H27-H29 are connected by two retaining walls. The retaining walls stand end to end and are approximately 2.5 m to 3 m in height and separate the properties at H28 and H29 from H27. As the fault rupture propagated north, it passed between the properties at H28 and H29 and between the retaining walls through a 16 cm gap. While the property at location H27 sustained significant damage due to concrete cracking and structural deformation, the retaining walls showed no clear signs of deformation. The foundation elements of the retaining walls are not known.

The performance of pier foundations under surface fault rupture conditions is an important question. Of the 8 investigated properties constructed on pier and grade beam foundations, the property at location H01 experienced the most damage. The surface rupture trace appears to have sheared the NE corner of the structure by passing between piers. Though it was not possible to enter the home, significant foundation and structural damage was visible from the exterior.