Geotechnical Extreme Events Reconnaissance (GEER)

Preliminary Observations of Surface Fault Rupture from the April 11, 2011 Mw6.6 Hamadoori Earthquake, Japan

(an aftershock of the March 11, 2011 Tohoku Offshore Earthquake, Japan)

by

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Introduction

One month following the great Mw9.0 Tohoku earthquake off the coast of northeastern Japan in March 2011, the Iwaki region of Fukushima Prefecture experienced a series of moderate to large aftershocks (JMA, 2011). The largest of these, the Mw6.6 Hamadoori earthquake, occurred on April 11, and was followed a few hours later by a Mw6.0 earthquake on April 12; both of these were centered beneath onshore Fukushima Prefecture (Figure 1). These earthquakes occurred at shallow crustal depths (about 12 km), and are considered to be aftershocks of the March 11 Mw9.0 Tohoku Offshore Earthquake (Figure 1). Other aftershocks originating in the shallow crust beneath the Iwaki area include a Mw5.8 on March 19, a Mw5.7 and a Mw5.4 on March 22, a Mw5.5 on April 11, and a Mw5.4 on April 13 (GCMT, 2011); these events generated locally strong ground motions and appear to be associated with displacement on normal faults in the shallow subsurface (JMA, 2011), but at this time are not associated with discrete surface fault rupture. However, field observations immediately following the April 11 Hamadoori earthquake demonstrated that this Mw6.6 aftershock generated surface fault rupture over a distance of at least 11 km in southeastern Fukushima Prefecture (Ishiyama et al., 2011a).

This preliminary report provides a summary of observations of surface rupture along the Idosawa (now, “Shionohira”) fault near the village of Tabito, Fukushima Prefecture, on April 23, 2011, twelve days after the Mw6.6 Hamadoori earthquake. The reconnaissance track and waypoints are shown in Figures 2 and 3. The reconnaissance was guided by initial reports available on the internet at the time of our departure from the United States on April 17, 2011 (Ishiyama et al., 2011a). These workers have since published updated observations in a larger area, including additional sites northwest of Tabito (Figure 4; (Ishiyama et al., 2011b). Wartman et al. (2011) also visited the Tabito-cho area and sites of possible fault rupture about 9 km southwest of the City of Iwaki (Figure 4).

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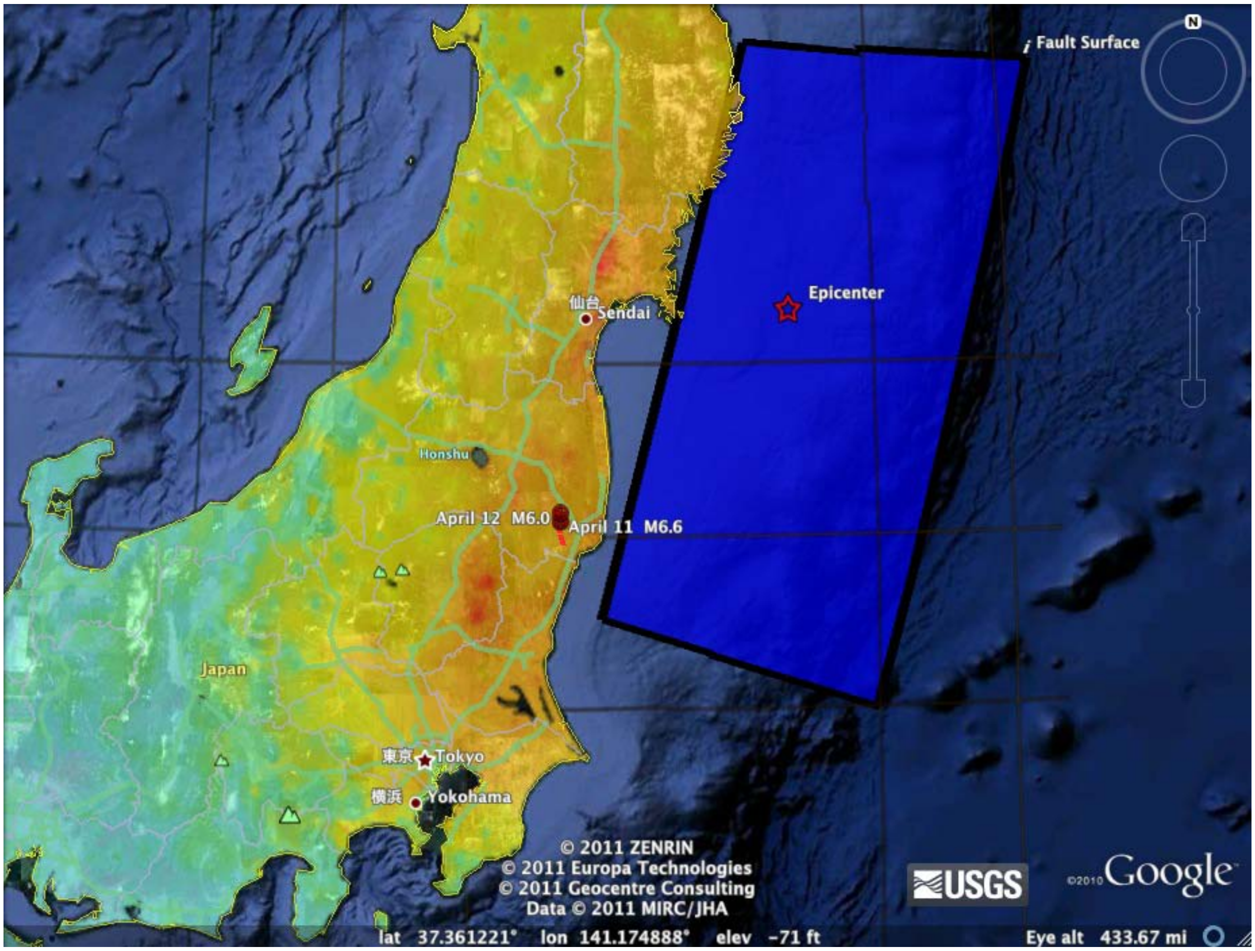

Figure 1: Locations of April 11, 2011 Mw6.6 Hamadoori Earthquake and related Mw6.0 event on April 12 (shown on USGS Shake Map for March 11, 2011 Tohoku Offshore Earthquake); surface fault rupture occurred in the vicinity of these epicenters.

Ishiyama et al. (2011a, accessed 4/16/11) noted that the fault experienced surface rupture along strands of the Idosawa fault, which was mapped previously by the Active Fault Research Group (1991) as a zone of numerous, north-northwest-striking inactive faults. Ishiyama et al. (2011b, accessed 4/29/11) provided additional field observations of the surface fault rupture, and named this feature the "Shionohira" fault after a small village northwest of Tabito-cho.

Ishiyama et al. (2011a, b) documented surface rupture along at least 11 km of the Shionohira fault, having primarily down-on-the-west normal displacement on a steeply west-dipping or vertical fault. The rupture involves a slight dextral component, and has a right-stepping *en echelon* pattern in its northern part, where it is west of the previously mapped trace of the Idosawa fault (Figure 4). The maximum vertical displacement reported to date (5/31/11) is 2.3 m at the village of Shionohira (N36.994˚, E140.684°), with most observations in the range of 0.8 to 1.5 m; the northernmost observations by Ishiyama et al. (2011b) indicated lesser amounts of vertical displacement (about 0.5 m) north of Shionohira. At this time, there are no reported observations of fault rupture south of the village of Tabito, although the Idosawa fault

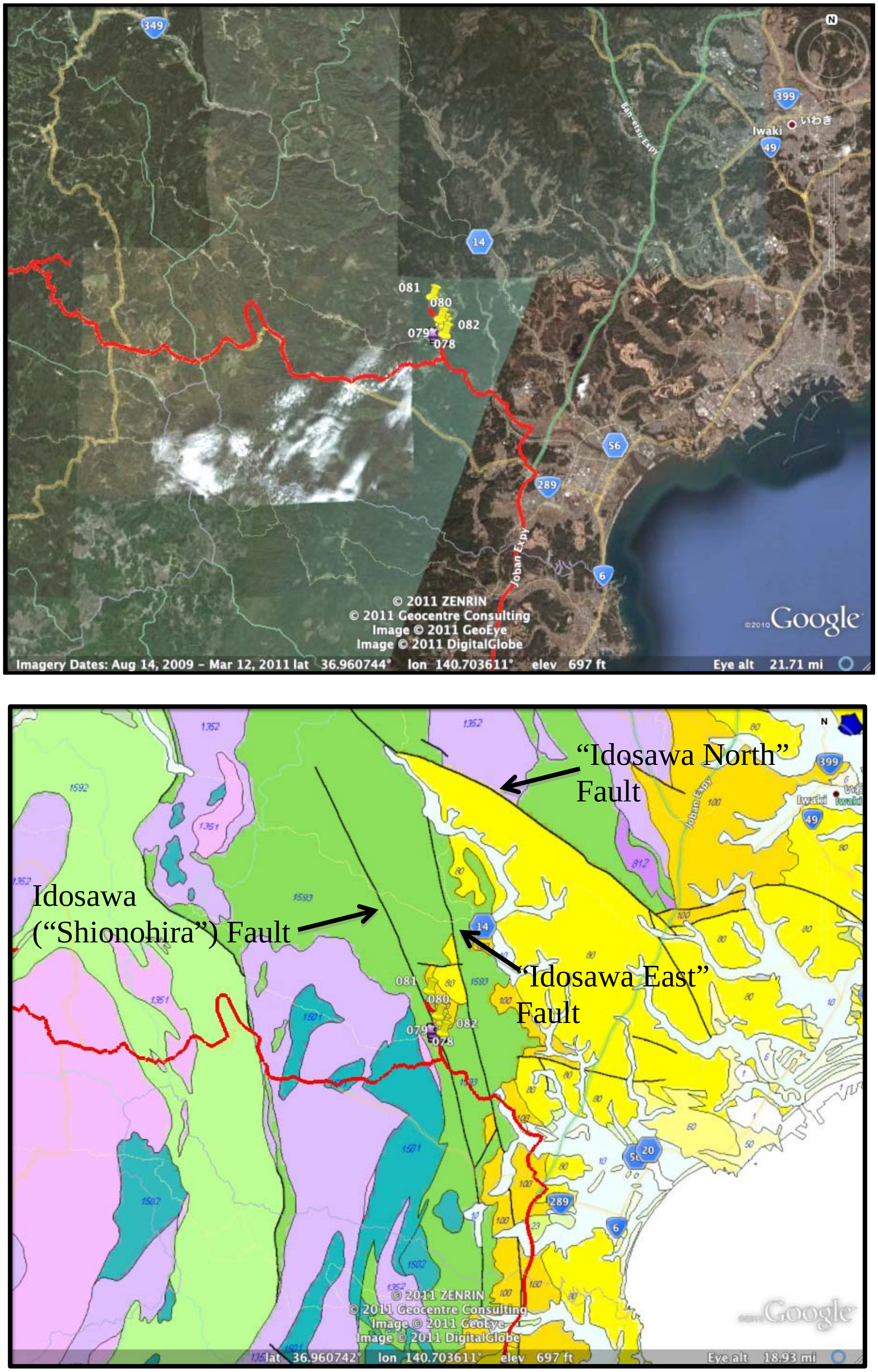

Figure 2: Field reconnaissance path (in red) and waypoints southwest of Iwaki performed by GEER team on April 23, 2011 (a) Google Earth image, (b) Geologic map (from GSJ, 2009).

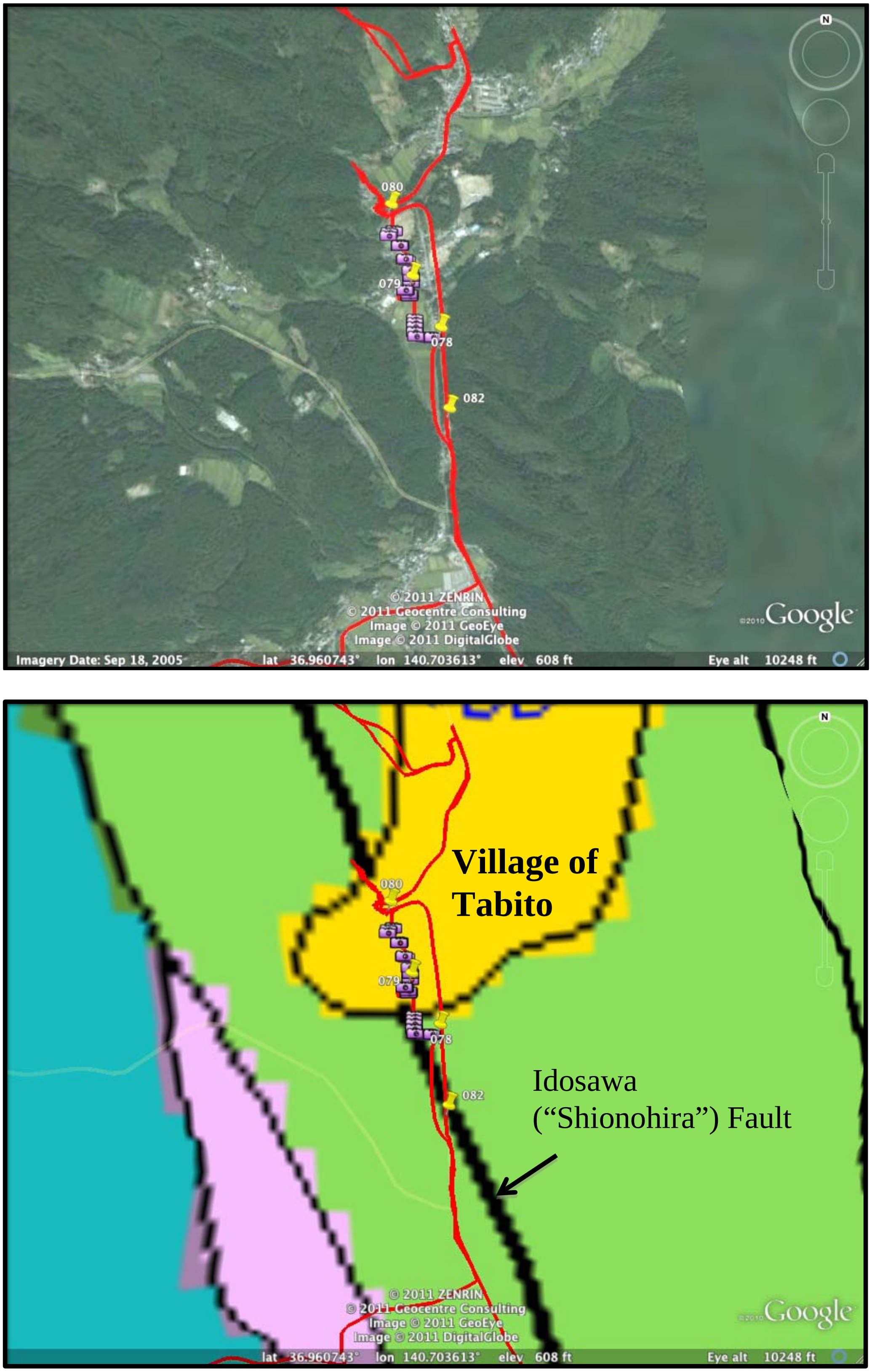

Figure 3: Field reconnaissance path (in red) and waypoints in village of Tabito performed by GEER team on April 23, 2011 (a) Google Earth image, (b) Geologic map (from GSJ, 2009).

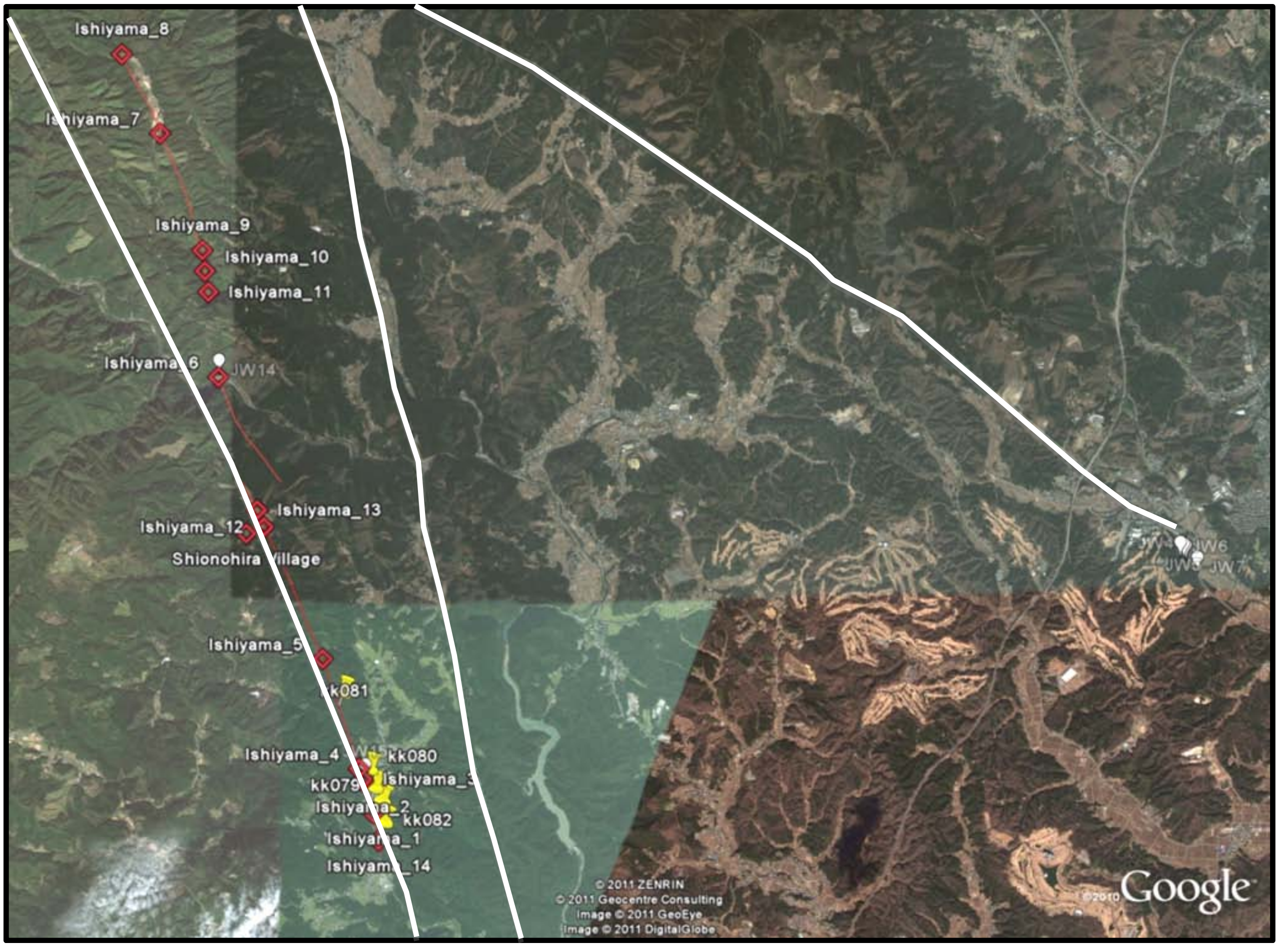

Figure 4: Summary of locations visited by the GEER Team (waypoints kk078 to kk082), Ishiyama and others (2011b), and the ASCE Team (waypoints jw3 to jw7 and jw14 to jw17; J. Wartman, personal communication). GSJ (2009) faults shown in thin white.

trace (as mapped by the Geological Survey of Japan, 2009) extends an additional 11 km southward. The total length of the trace mapped by the GSJ (2009) and termed the Shionohira fault by Ishiyama et al. (2011b) is 22 km. In addition, there is a parallel fault trace located about 1 km east of the Shionohira fault (GSJ, 2009; Figure 4). This latter fault has a total length of about 23 km, strikes north-northwest (N10˚W), and appears to displace the same suite of rock units as does the Shionohira fault. For simplicity, this fault is referred to herein as the “Idosawa East fault.” Lastly, GSJ (2009) identified a fault that strikes about N45˚W and is located northeast of the both the Shionohira and Idosawa East faults (Figure 2). This fault has a total length of about 24 km and may be associated with local surface rupture (J. Wartman, Personal Communication, 2011); it is referred to herein as the “Idosawa North fault” (Figure 4).

Field Observations

Our field reconnaissance of the Shionohira fault rupture on April 23, 2011 included observations in the vicinity of the village of Tabito, as guided by Ishiyama et al. (2011a, b). This summary of observations describes features near Tabito from north to south. In the rugged topography northwest of Tabito, a one-lane asphalt road extends northwest from the main Tabito Valley road, and is crossed by the fault at locality kk081 (Figure 5). At this locality, the fault scarp is distinct and nearly vertical (Figures 6 through 8); it extends with a strike of about N10˚W across rugged topography, suggesting a steep near-surface fault dip. Slickensides on the fault plane exposed in the scarp face (where it deforms the one-lane road) plunge steeply (about 85˚) but slightly to the south (Figure 8), suggesting a minor dextral component of slip. At the road crossing and the adjacent ridge crest directly to the north, the scarp faces uphill and there is no evidence that it is a product of landsliding. The presence of the 1.5-m-high scarp in this bedrock terrain, and the continuity with features described below, shows that the scarp is a tectonic feature related to surface rupture, rather than landsliding or liquefaction-related slope instability.

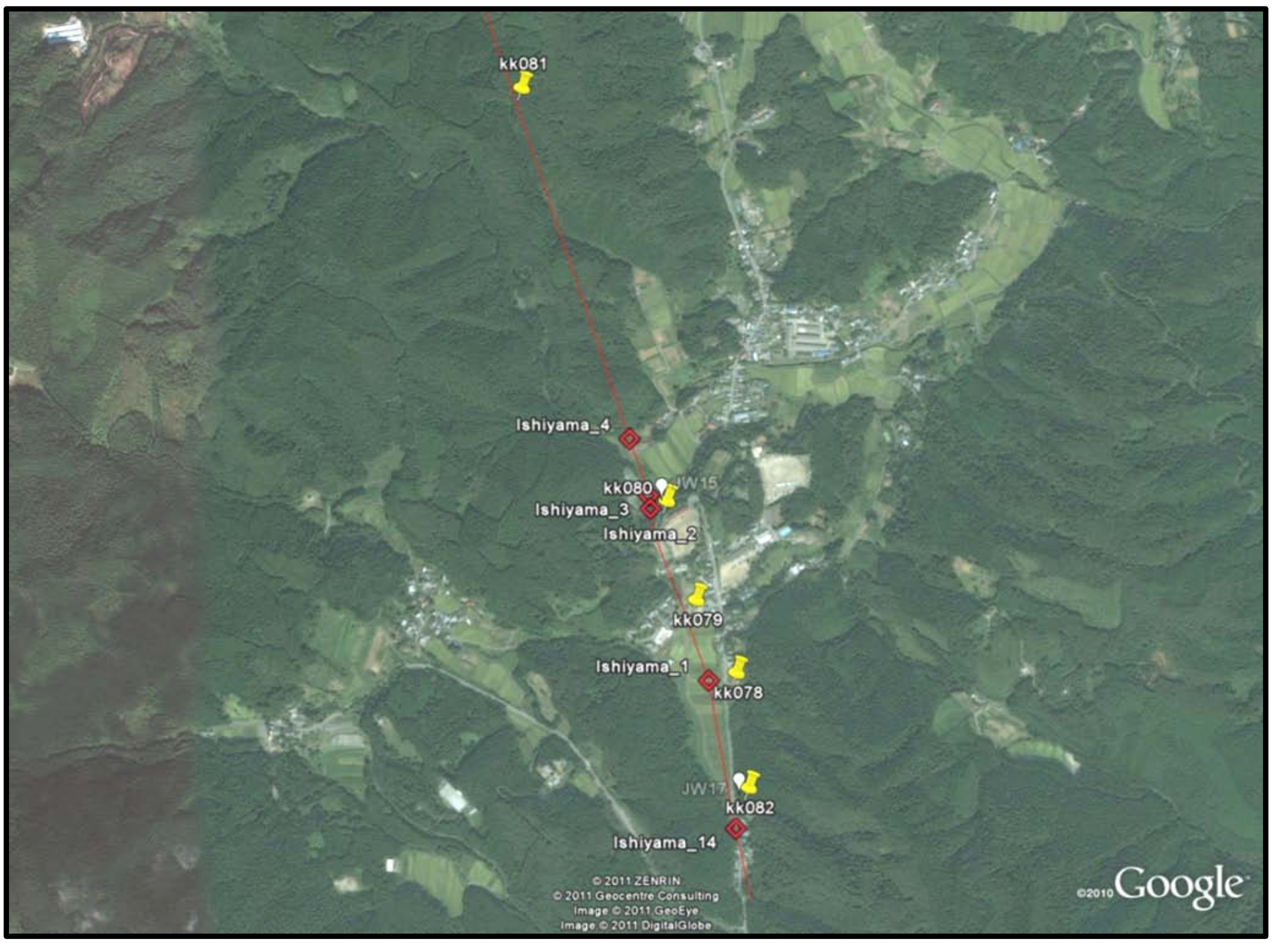

Figure 5: Generalized fault map of surface rupture along the Shionohira fault in the village of Tabito, Fukushima Prefecture, Japan, showing waypoints noted by Ishiyama et al., (2011a; Ishiyama_1 to _4), the GEER team (kk078 to kk081), and the ASCE Team (jw15 and jw17).

Figure 6: Photograph looking north along surface rupture at waypoint kk081 (N36.9735°, E140.6978°; April 23, 2011). West-facing fault scarp is approximately 1.5 m high along a near-vertical plane developed in weathered bedrock. Dr. Tadahiro Kishida is at the base of the scarp near the crest of the east-west-trending ridge.

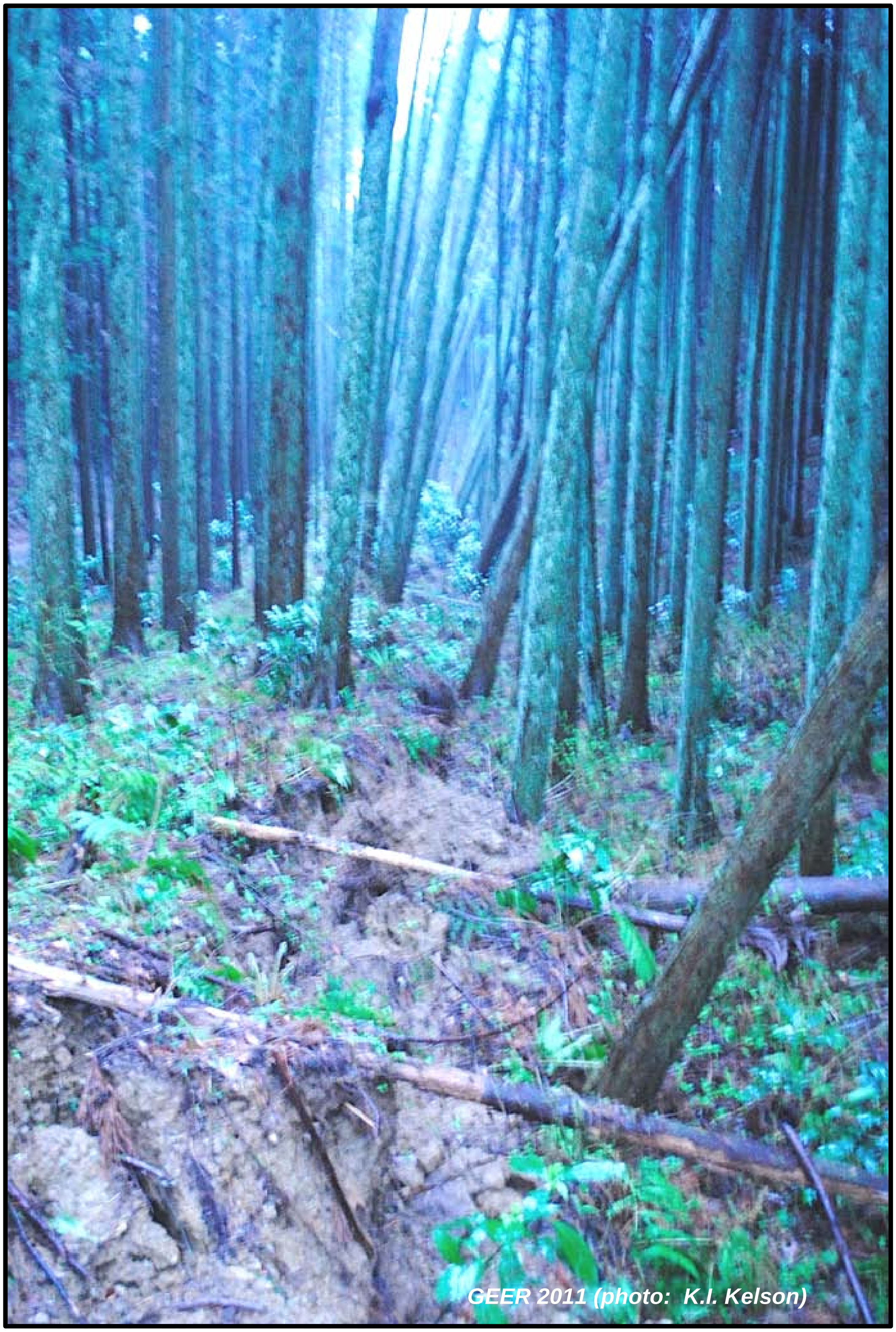

Figure 7: Photograph looking south along surface rupture at waypoint kk081 (N36.9735°, E140.6978°; April 23, 2011). Rupture traverses forest with primarily vertical trees, except where fault scarp caused westward tilting of trees along fault trace

Figure 8: Photograph looking east at scarp face at waypoint kk081 (N36.9735°,E140.6978°; April 23, 2011). Slickensides on striated bedrock surface plunge steeply south (about 85˚ toward 170˚), indicating dominantly vertical displacement with slight dextral offset. Roadside drainage box culvert on right side of photograph also shows component of dextral offset.

Approximately 0.8 km to the south of locality kk081 (Figure 5), the fault extends across the floodplain of Bettougawa Creek (Figures 9 and 10, Ishiyama et al., 2011a, b). West-down displacement on the western side of the scarp resulted in an uphill-facing scarp, ponding of the creek west of the fault, and flooding of the low floodplain (Figure 11). Deformation of the alluvium and agricultural fields in the valley suggests west-down net vertical displacement of about 1.2 m and a minor component of right-lateral offset. The fault strand is distinct here, lacks substantial off-fault folding, and appears to be continuous with the scarp at locality kk081 to the north.

South of Bettougawa Creek, the fault rupture extends across Tabito Valley Road in two locations (localities 2 and 3 of Ishiyama et al., 2011a; Figure 5). The roadway has a hairpin turn as it climbs southward from the Bettougawa Creek floodplain toward a bedrock ridge, and the fault rupture cuts twice across this hairpin turn. Both of these localities include prominent west-facing fault scarps across the road surface; both had been repaired prior to our visit (Figures 12 through 14). Ishiyama et al. (2011 a) showed photographs of these scarps prior to repair, and noted vertical displacement of about 1.2 m and dextral offset of about 0.3 m.

The fault rupture extends from these roadway scarps south to the Tabito Middle School (locality kk080 in Figure 5), which is located on a saddle in the crest of an east-plunging ridge underlain by bedrock (Figure 5). The presence of the scarp transverse across the ridge supports a tectonic origin rather than liquefaction or slope instability. School buildings and facilities located across the fault trace are deformed (Figures 15 through 17). The gymnasium straddles a

Figure 9: Photograph looking northeast at west-facing scarp traversing floodplain of Bettougawa Creek (N36.9961˚, E140.7008˚; April 23, 2011). Scarp developed on agricultural fields that originally sloped gently east; plastic sheeting covered a crop row was extended and displaced.

Figure 10: Photograph looking east at west-facing scarp traversing floodplain of Bettougawa Creek (N36.9961˚, E140.7008˚; April 23, 2011; also Location 4 of Ishiyama et al., 2011a, b). Vertical displacement ≈1.2 m, minor dextral slip suggested by offset of crop rows and levee.

Figure 11: Photograph looking northeast at west-facing scarp traversing Bettougawa Creek (N36.9961˚, E140.7008˚; April 23, 2011; also Location 4 of Ishiyama et al., 2011a, b). Uplift on eastern side of fault resulted in ponding of creek and flooding of low terrace adjacent to channel.

Figure 12: Photograph looking east at west-facing scarp developed in roadway between Bettougawa Creek and Tabito Middle School (waypoint jw15; N36.9649˚, E140.7015˚; April 23, 2011; also Location 3 of Ishiyama et al., 2011a, b). Ishiyama et al. (2011a) noted scarp height of approximately 1.1 m and dextral offset of approximately 0.3 m at this location. Fault rupture produced uphill-facing fault scarp across the roadway here.

Figure 13: Photograph looking north at locality jw15 (Locality 3 of Ishiyama et al. 2011a, b), from locality kk080 (N36.9647˚N, E140.7016˚; April 23, 2011; also Location 2 of Ishiyama et al., 2011a, b). Repaired asphalt indicates location of fault scarp developed in roadway. Bettougawa Creek in distance, between roadway and forested slope.

Figure 14: Photograph looking east at west-facing scarp developed in roadway between Bettougawa Creek and Tabito Middle School (waypoint kk080; 36.9647˚N, 140.7016˚W; April 23, 2011; also Location 2 of Ishiyama et al., 2011a, b). Fault rupture produced downhill-facing fault scarp across the roadway at this location.

Figure 15: Photograph looking east at Tabito Middle School gymnasium (locality kk080; N36.9640˚, E140.7015˚; April 23, 2011). Damaged gymnasium on right side of photograph is within broad (100 m) wide zone of westward tilting (asphalt in middle ground). Closest traffic cone is located near base of west-dipping fold panel.

Figure 16: Photograph looking south at Tabito Middle School gymnasium (locality kk080; N36.9640˚, E140.7015˚; April 23, 2011). Doorframe of gymnasium is deformed and is tilted approximately 3˚westward.

Figure 17: Photograph looking south at Tabito Middle School pool (36.9635˚N, 140.7017˚W; April 23, 2011). West-facing fold panel includes the western part of the pool; note ponded water in only the eastern part of pool. Field observations from area directly south of pool (in background of this photograph) indicate a 100-m-wide zone of distributed minor normal faults.

broad fold directly on projection with the fault scarps developed in the roadway (see above), and is surrounded by a cracked and tilted asphalt surface (Figure 15). The gymnasium is tilted about 3˚ westward, and no longer has rectangular doorframes or a level entryway (Figure 16). The building was not entered during our reconnaissance. Directly south of the gymnasium, the school pool is also deformed and tilted gently westward (Figure 17). Both the pool and gymnasium overlie the zone of faulting but do not exhibit evidence of distinct surface fault rupture; instead, these structures are tilted across a broad zone of deformation. It is not clear at this point if the buildings were positioned in an area that fortunately experienced distributed deformation, or if the buildings influenced the pattern and style of surface deformation.

Directly south of the Tabito Middle School, the fault rupture is slightly more complex, consisting of several minor normal faults arranged in an *en echelon* pattern over a width of approximately 100 m. The fault zone includes a couple of residential buildings, and appears to extend either through or around these modest, one-story structures. No substantial damage to these structures was observed during this reconnaissance, which did not include entry into the buildings. The numerous small normal-fault ruptures were observed in recently plowed row-crop gardens, and probably are very ephemeral. Active erosion of the fault features was observed during our reconnaissance (in high-intensity rainfall).

Locality kk079 (Figure 5) approximates the northern end of a linear valley currently occupied by several rice fields, within which Ishiyama et al. (2011a, b) identified the fault rupture. At the northern end of the valley, the rupture has an overall right-stepping *en echelon* pattern, and is a broad (100 m) zone of folding (Figure 18). In the central and southern parts of the valley, the deformation is more distinct, occurring over a width of about 50 m or less (Figures 19 and 20), although the scarp was formed primarily by folding of near-surface materials. We interpret that this difference in fault-scarp morphology is related to the characteristics of near-surface materials, such that the unconsolidated alluvium in the valley has deformed with a more ductile character than the areas underlain by shallow bedrock (i.e., north of the middle school). As noted by Ishiyama et al. (2011 a, b), the scarp traversing the rice fields exhibits about 0.8 to 1.2 m of vertical displacement, although this may be a minimum if displacement across the entire zone of deformation was not measured.

At the southern end of valley containing the rice fields, the fault strand obliquely crosses the main highway again, and deformation has been repaired. We observed fresh, west-facing scarps in asphalt driveways adjacent to the highway (Figure 21), but were unable to determine net displacements. These scarps are collinear with features observed across the rice fields and with repairs that were being completed in the roadway and a concrete-lined river channel west of the roadway. We interpret that the locations of these repairs reflect the pattern of surface deformation at the southern end of the Tabito valley. We were not able to make observations in the area south of the Tabito valley (because of darkness and rain), although it seems likely that the fault rupture extended farther south.

Figure 18: Photograph looking south across northern end of deformed rice field (near locality kk078; N36.9622˚, E140.7023˚; April 23, 2011; also Location 1 of Ishiyama et al., 2011a, b). West-facing fold is shown by grassy strips; the folding narrows southward to a more distinct fault scarp in distance.

Figure 19: Photograph looking east at fold/fault scarp developed on deformed rice field (near locality kk078; N36.9611˚, E140.7024˚; April 23, 2011), and ground cracking present on crest of fault scarp. Ishiyama et al. (2011a, b) noted a scarp height of 0.8 m and dextral offset of about 0.3 m; total vertical deformation is probably greater than 0.8 m because of distributed folding away from distinct fold/fault scarp.

Figure 20: Photograph looking south across deformed rice field (locality kk078; 36.9608˚N, 140.7030˚W; April 23, 2011). West-facing fold panel shown by grassy borders of the fields; ground cracking represents minor graben formation on footwall of normal fault, as also noted by Ishiyama et al. (2011a, b).

Figure 21: Photograph looking east at scarp across asphalt driveway at the southern end of the Tabito valley (near locality kk082; N36.9569˚N, 140.7040˚W; April 23, 2011). Scarp height approximately 0.5 m, although the total net vertical displacement is not known at this location.

Comparison with Coseismic (Aftershock) Interferogram

Coseismic ALOS PALSAR interferograms were processed at the University of Liverpool to investigate possible locations and patterns of surface deformation resulting from the onshore aftershock sequence. We interpret the pattern of coseismic deformation during the mid-April aftershocks by processing an ALOS PALSAR image pair on Track 403 with start date on March 3 (16 days before the first moderate aftershock in this area) and end date on April 18. Processing of these digital images followed standard processing protocols, as described in Ryder et al. (in review, 2011). After processing, a long-wavelength quadratic function across the interferogram was removed to minimize the coseismic signal from the March 11 Tohoku mainshock to the northeast.

The wrapped interferogram in Figure 22 shows several distinct, and in some cases overlapping, sets of phase fringes, which can be associated with several of the post-March 11 quakes centered in the onshore area of southeastern Fukushima Prefecture. On Figure 22, aftershocks greater than Mw5.4 are numbered in temporal sequence from 1 to 7, with the Mw6.6 Hamadoori shown as event number 4. The most distinct phase shift is spatially associated with this largest aftershock, and suggests deformation on a northwest-striking fault. Other fringe discontinuities suggest possible surface deformation (although to a lesser degree) associated with the Mw6.0 earthquake on April 12 (number 6 on Figure 22) as well as all the other moderate-magnitude aftershocks shown on the figure. These data support the interpretation that the upper crustal area in southeastern Fukushima Prefecture experienced normal faulting, block tilting, and discrete surface rupture in the shallow crust for several weeks following the March 11 mainshock. In

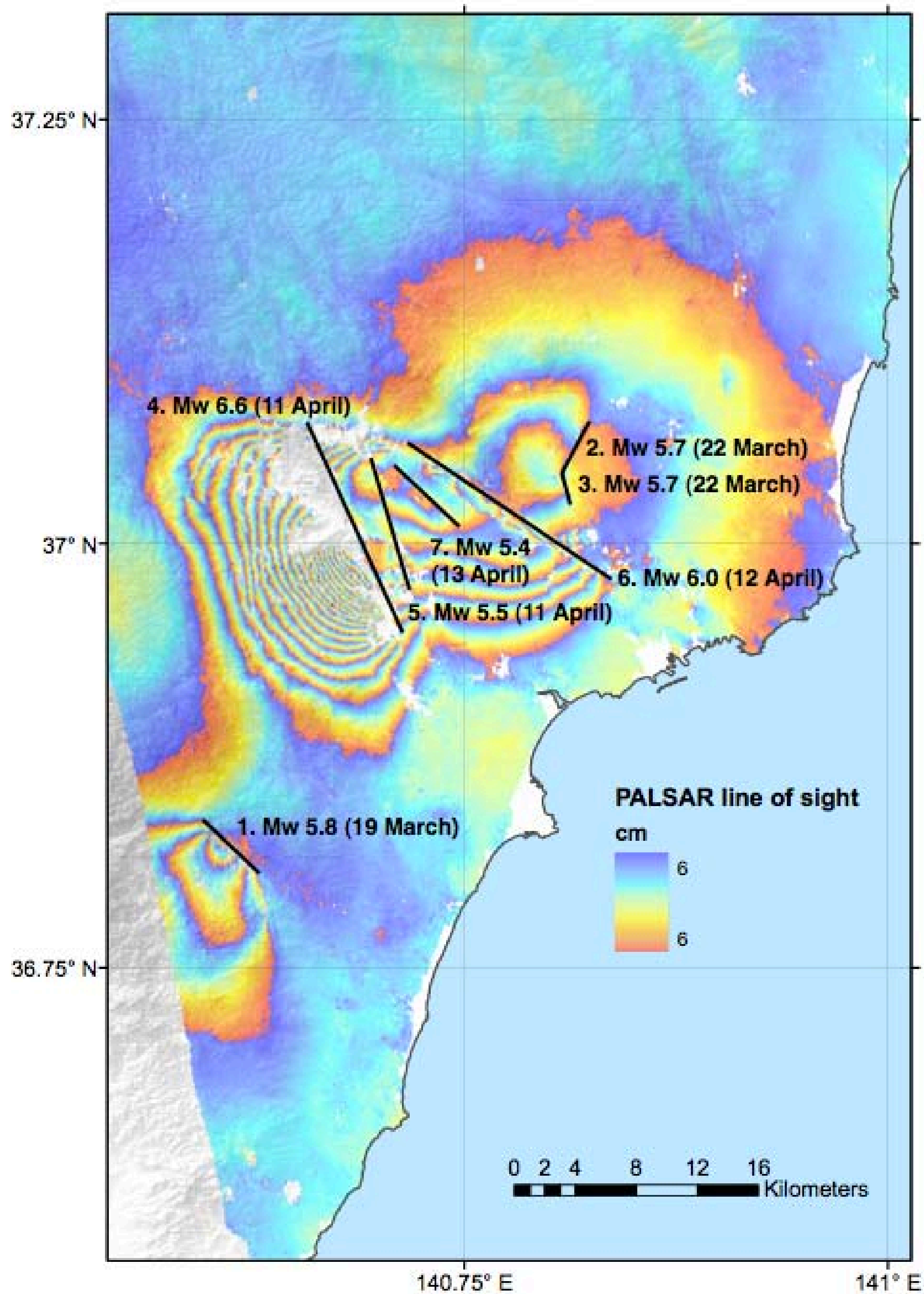

Figure 22: Interferogram generated from ALOS PALSAR (InSAR) data by University of Liverpool, showing pattern of surface deformation between mid-March and mid-April, 2011. Numbered events 1 through 7 show interpretation of deformation associated with noted aftershocks.

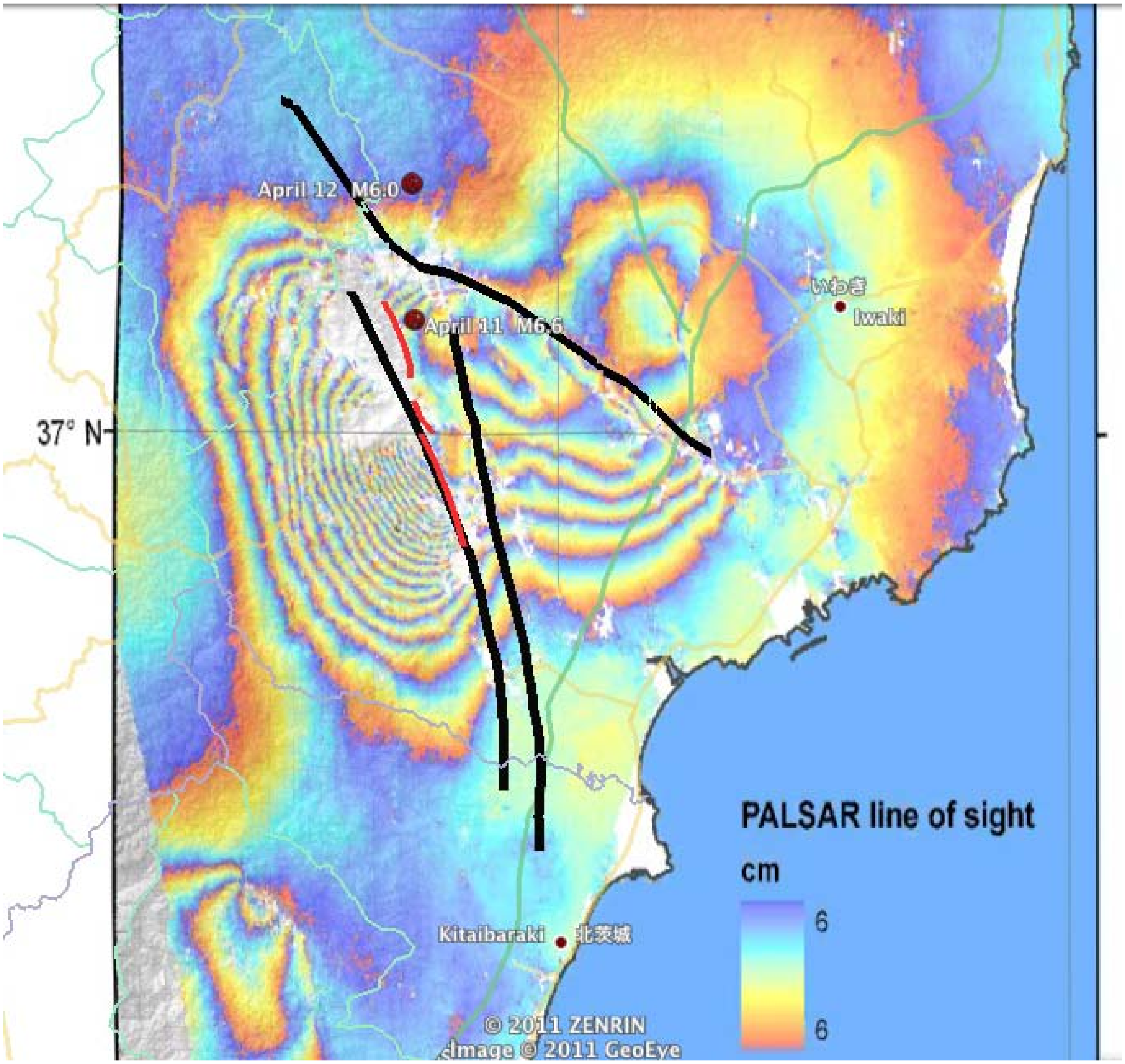

Figure 23: Interferogram generated from ALOS PALSAR (InSAR) data by University of Liverpool, showing pattern of surface deformation between mid-March and mid-April, 2011. Epicenters of the Mw6.6 April 11 and Mw6.0 April 12 aftershocks from GCMT (2011); fault traces mapped by GSJ (2009) shown in black. Documented surface rupture shown in red, with southern part of rupture coincident with Shionohira fault (this report, Ishiyama et al., 2011a, b).

particular, the area first experienced small amounts of deformation in the southwest on March 19 and in the northeast soon after (from two aftershocks on March 22), followed by a cluster of moderate earthquakes (and documented surface rupture) in the intervening area from April 11 to 13 (Figure 22). Speculation could be made that the mid-April cluster of earthquakes (and surface rupture) represent the response of the upper crust to changes in local stress fields resulting from the mid-March mainshock and subsequent moderate-magnitude aftershocks.

Figure 23 shows the same interferogram focused on the area containing the Shionohira fault identified by Ishiyama et al. (2011a, b) and the “Idosawa East” and “Idosawa North” faults identified herein; these mapped faults are shown as black lines. On this figure, red lines indicate the locations of documented surface rupture along the Shionohira fault, based on observations by our team and Ishiyama et al. (2011a, b). This interferogram clearly shows coincidence of the surface rupture along the Shionohira fault with deformation defined by the InSAR data. In addition, Figure 23 suggests possible surface deformation in the vicinity of the Idosawa East fault, although the degree of phase shift is less than that along the Shionohira fault, and thus may not be perceptible at the ground surface via field reconnaissance. Lastly, the interferogram in Figure 23 strongly suggests the occurrence of surface deformation along or near the Idosawa North fault, which likely occurred during the Mw6.0 April 12 aftershock (Figure 22). The possibility of surface fault rupture along this structure is not known at this time, although observations by J. Wartman (University of Washington, personal communication, May 19, 2011) suggest that the fault may have displaced Highway 14 with down-on-the-northeast relative movement (site jw7, Figure 4). Based on the InSAR data, the amount of surface deformation, if any, would appear to be less than that documented along the Shionohira fault as noted above.

We conclude that the pattern of deformation exhibited by the satellite data, in conjunction with the field observations of surface rupture, provide evidence of post-mainshock, distributed re-adjustments of the shallow crust in the hanging wall of the subduction zone, and that these adjustments occur along or near previously mapped upper crustal faults. An important question derived from the data and analysis presented herein is whether the structures that appear to have not experienced some deformation are, in the present (rearranged) stress field, ready and “primed” for deformation during possible aftershocks in the near future.

Conclusions

The April 11 Mw6.6 Hamadoori aftershock of the March 11 Mw9.0 Tohoku earthquake produced surface fault rupture along the south-central part of a previously mapped fault trace, herein referred to as the Shionohira fault. The fault rupture provides evidence of west-down normal faulting on a fault that strikes approximately N10˚W and has a steep dip. The amount of displacement ranges from about 0.8 to 2.3 m, with most of the scarp showing about 1.2 to 1.5 m of vertical deformation. There is about 0.3 m of dextral offset as well. Where present in shallow bedrock, the fault rupture was relatively distinct and linear; however, where present in unconsolidated alluvium the rupture is characterized by a fold scarp and hanging-wall cracking. In a few places, buildings or other engineered structures were present in the zone of deformation, although none experienced collapse. Limited measurements suggest that the structures were tilted as much as about 3˚ westward but did not experience structural rupture. The structures fared surprisingly well, although most of these appeared to have been located in areas of distributed deformation; it is not clear whether this was merely a fortunate occurrence or if the structures themselves influenced the pattern and width of near-surface faulting and folding. Lastly, the pattern of surface deformation documented from field reconnaissance is consistent with satellite-based definition of regional crustal block re-adjustments following the main Mw9.0 suduction-zone earthquake. We conclude that the pattern of deformation exhibited by the satellite data, in conjunction with the field observations of surface rupture, provide evidence of post-mainshock, distributed re-adjustments of the shallow crust in the hanging wall of the subduction zone, and that these adjustments occur along or near previously mapped upper crustal faults.

Recommendations for Future Research

(1) Several sites visited during our reconnaissance on April 23 could yield important information on how engineered structures respond to shallow crustal normal faulting:
- Tabito Middle School gymnasium should be evaluated further for damage and interrelationships with faulting and folding;
- Residential structures directly south of Tabito Middle School should be assessed for possible rupture damage or influences on rupture patterns;
- Also, about 6 km south of Tabito, the Shionohira fault is at or near a large, 83-m-high earthen dam (N36.906˚, E140.718˚, built in 1970); the proximity of the fault to this structure should be evaluated.

(2) The regional character and extent of the rupture should be evaluated; in particular:
- The southern extent of surface deformation should be delineated;
- Documentation of the along-strike variability of total displacement should be completed, in order to define the overall rupture pattern and at-a-point variability;
- Documentation of the across-strike pattern of total deformation should be completed in areas of different substrate materials; for example, the pattern of the total cross-fault deformation should be documented for areas underlain by unconsolidated alluvium, by shallow bedrock, and cases in between these end members.

(3) Other possible surface-rupture locations should be checked and documented, including:
- Possible surface rupture along the Idosawa North fault, especially near its southeastern end where J. Wartman observed a surface scarp across Highway 14 (site jw7; Figure 4);
- Selected localities in alluvium along the Idosawa East fault (Figure 2).

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