

SURFACE RUPTURE MAPPING OF THE 2019 M6.4 AND M7.1 RIDGECREST EARTHQUAKE SEQUENCE ON LIDAR AND ORTHOIMAGERY

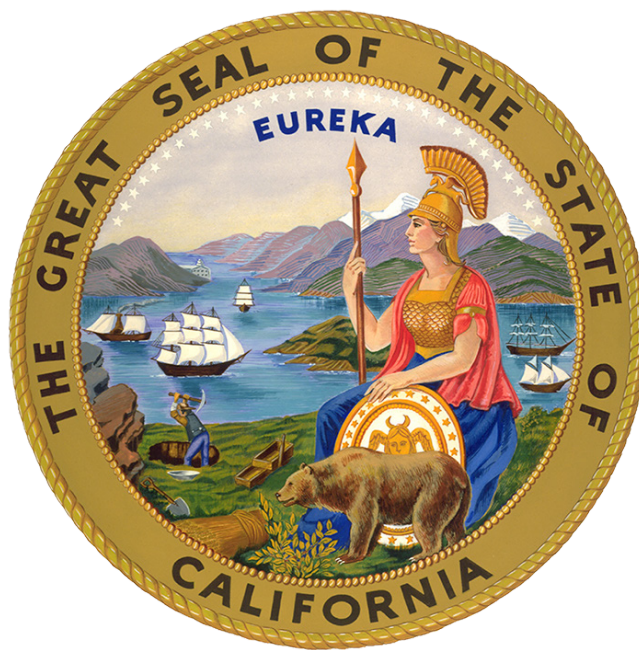
SPECIAL REPORT 257

Carla Rosa, Timothy Dawson, and Reva Kakaria



California Geological Survey
California Department of Conservation
Sacramento, California

February 2, 2024



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ABSTRACT

The M_w 6.4 and M_w 7.1 2019 Ridgecrest Earthquake Sequence produced complex surface rupture and ground deformation along two distinct fault zones with mapped rupture lengths extending 18 km and 50 km, respectively. Immediate post-earthquake field reconnaissance allowed for efficient flight-line planning for the simultaneous collection of medium- to high-resolution aerial lidar (25 to 80 pulses per square meter (ppsm), respectively) and airborne optical imagery along the rupture (Hudnut et al., 2020). We produced a comprehensive surface rupture map using orthoimages and hillshades derived from these data, documenting visible features with qualitative descriptions and an associated catalog of attributes. We mapped the full extent of surface rupture at a consistent digital screen scale (1:300 – 1:500), the largest scale at which imagery resolution is not degraded. This allowed for centimeter-scale features to be resolved, although mapping using orthoimagery was somewhat limited by image resolution, variable image quality, and time available to map at a large scale. Both fault zones consist of primary fault strands with linear cracks continuous along strike, broad regions of distributed fractures, and well-defined scarps as high as 3 m. The mapping approach was designed to capture the width of these rupture zones and zones of cracking and to characterize the rupture's expression through varying terrain, such as hillslopes, fan surfaces, and relatively flat playa surfaces. These aerial lidar and orthoimagery datasets allow for comprehensive and uniform documentation of surface rupture and ground deformation features and are complementary with previous mapping datasets. Features mapped in our dataset generally have greater location accuracy and more specificity to fine-scale expression when compared with previous mapping datasets. Whereas our mapping does capture deformation in previously undocumented areas, it can be less comprehensive compared with ground-based and geodetic observations in the near-field. Our dataset of surface rupture features will be potentially useful for longer term, geomorphic-based fault evaluation as we continue to learn from mapping of earthquake ruptures that are the primary evidence of large $>M_w$ 6.0 earthquakes. Characterizing zones of deformation for the 2019 Ridgecrest Earthquake Sequence, important for improving fault displacement and seismic hazard assessment and understanding fault mechanics, benefits from a paired approach using both high-resolution lidar and orthoimagery in addition to established ground-based collection methods.

INTRODUCTION

Ridgecrest Earthquake Sequence Background

The Ridgecrest Earthquake Sequence (RES) consisted of two earthquake events, a foreshock on July 4th and a mainshock on July 5th, 2019, local time, occurring along two orthogonal cross-faults (Figure 1). The M_w 6.4 event on July 4th occurred on what now has been named the Salt Wells Valley Fault Zone. This event was characterized by a left-lateral, nearly continuous, northeast-southwest striking rupture 18 km long (Ponti et al., 2020). The M_w 6.4 event had widely distributed surface rupture at the southwestern end and exhibited little vertical displacement, with a left-step at the northeastern end with extensional displacement. Left-lateral displacements were measured as high as ~1.6 m, with the largest displacements occurring near the center of the rupture, southwest of the intersection with the M_w 7.1 rupture (Ponti et al., 2020; DuRoss et al., 2020).

The July 5 mainshock was a M_w 7.1 event on the Paxton Ranch Fault Zone (Figure 1). This second event was characterized by right-lateral movement along a northwest striking, approximately 50 km long rupture (Ponti et al., 2020). Horizontal displacements as large as 7 m were observed in the field near the epicenter (DuRoss et al., 2020; Ponti et al., 2020). Down-to-the-west vertical separations were also observed along strike of the rupture; most of these were less than 1 m, but several reached 2-4 m (Ponti et al., 2020; DuRoss et al., 2020). The rupture zone of the M_w 7.1 event was complex, consisting in places of multiple subparallel and anastomosing traces, some as far as a kilometer or more from the primary rupture trace. At the north end, the predominant northwest strike of the rupture became more northerly. As the rupture died out northward, the rupture pattern became discontinuous and complex, composed of numerous short discrete traces striking northwest and cross faults striking northeast. At the southern end, south of the intersection with the M_w 6.4 event, the rupture occurred along one main trace, with a secondary trace, ~2 km to the west, paralleling it for ~6 km.

Both fault zones are characterized by multiple fault strands and conjugate faults that exhibited vertical displacement and various ground deformation features such as en echelon fractures, surface cracks, and moletracks. Zones of ground deformation extended hundreds of meters from the primary fault ruptures, with additional surface manifestations including liquefaction-related deformation and sand boils in playa areas (Ponti et al., 2020). The two events triggered slip along ~20-25 km of the Garlock fault (Barnhart et al., 2019), as well as on the Little Lake Fault Zone and other previously unmapped faults (Hernandez and Dawson, 2019; Bilham and Castillo, 2019).

Regional Setting

The RES occurred in the southern Walker Lane, within the Eastern California Shear Zone (ECSZ) (Figure 1), with surface rupture from the mainshock extending to ~4.5 km north of the Garlock Fault (Milliner and Donnellan, 2020). The Walker Lane – ECSZ is a transtensional belt of discontinuous faults with predominantly right-lateral shear that accommodates 15-25% of the deformation within the Pacific – North American plate boundary, which is transferred from the San Andreas Fault through the ECSZ and the Walker Lane (Rockwell et al., 2000; Wesnousky, 2005;

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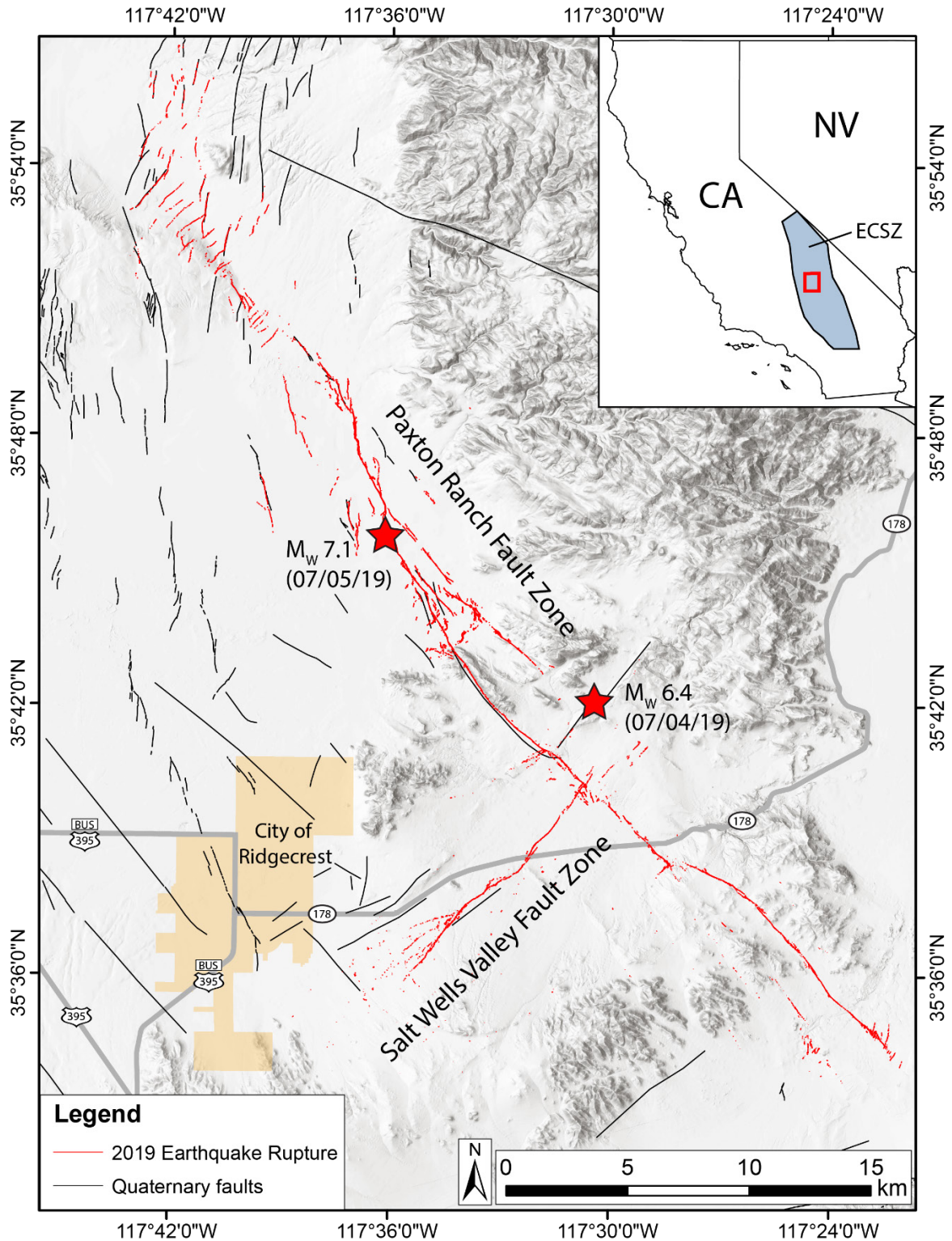


Figure 1. Regional map depicting project area with surface ruptures and ground-deformation features associated with the Mw 6.4 and Mw 7.1 Ridgecrest Earthquakes on the Salt Wells Valley and Paxton Ranch Fault Zones, respectively (red lines). Red stars indicate approximate epicentral locations, with earthquake date (local time), for each event. The black lines represent previously mapped Quaternary faults (USGS and CGS, 2023) in the region. Also shown are highways 395 and 178 (grey lines) and the City of Ridgecrest (orange polygon). Inset depicts location of main image (red box) and approximate extent of the Eastern California Shear Zone (ECSZ) (grey polygon). Base source: Airbus, USGS, NASA, CGIAR, NLS, OS, NMA, Geodatastyrelsen, GSA, GSI and the GIS User Community.

Faulds et al., 2005; Frankel et al., 2008). Surface ruptures from the RES occurred primarily along previously unmapped faults east and southeast of the Little Lake and Airport Lake Fault Zones, respectively (Wills, 1988; Wills, 1989; USGS and CGS, 2023) (Figure 1). Approximately 35% of the surface rupture from the RES occurred on previously mapped faults (Thompson Jobe et al., 2020).

Response Effort

Initial field response efforts following both earthquakes focused on documenting surface faulting and ground deformation features. This was carried out by dozens of geologists and other scientists from the California Geological Survey (CGS), United States Geological Survey (USGS), National Aeronautics and Space Administration (NASA), U.S. Navy, and various consulting firms and academic institutions (Ponti et al., 2020). Ground- and helicopter-based reconnaissance immediately following the earthquakes identified the extent and pattern of fault rupture. The aerial component of the response was critical in confidently locating the extent of the ruptures. These data were then collated by the CGS and USGS and used to support and plan response efforts, including further field data collection efforts, instrument deployments, and flight-line planning for lidar and aerial imagery collection (Hudnut et al., 2020; Pickering et al., 2019). Because of the region's arid environment, surface faulting and shaking-related ground deformation features remained preserved for months following the earthquakes, which allowed for effective post-event aerial imagery and lidar collection.

Related Investigations

Remote Mapping Efforts

Several studies following the RES used various sources of imagery to map surface fault ruptures in detail.

Pierce et al. (2020) presented a portion of their initial mapping of surface ruptures of the southeastern terminus of the M_w 7.1 event. Their work included the collection of more than 20,000 high-resolution aerial photos collected along ~12 km of the southeastern terminus of the M_w 7.1 event and ~8 km of the M_w 6.4 event (Pierce et al., 2020). These photos were acquired from low-flying (~30-60 m above ground) drone surveys with resolutions ranging from ~1 to 20 cm/pixel and they mapped at scales from 1:40 to 1:150 (Pierce et al., 2020).

Donnellan et al. (2020) collected six targeted structure-from-motion surveys covering two 500 x 500 m areas from the southern region of each event of the RES, which they used to create a detailed map of surface ruptures. They focused on mapping surface ruptures, with their images zoomed to cover a ~20 x 20 m area, to measure post seismic slip over time.

Milliner and Donnellan (2020) utilized optical satellite imagery collected daily from Planet Labs, which has a 3 m resolution, to create horizontal deformation maps. From these deformation maps, Milliner and Donnellan (2020) created a dataset of fracture mapping to discern deformation resulting from the M_w 6.4 foreshock rupture prior to the M_w 7.1 mainshock.

Rodriguez Padilla et al. (2021) developed high-resolution maps of surface rupture of the RES utilizing aerial imagery from both Hudnut et al. (2020) and Pierce et al. (2020). While their study used the same dataset as ours (i.e., Hudnut et al., 2020), Rodriguez Padilla et al. (2021) focused on five distinct sections of the earthquakes' ruptures and not the entire extent. Additionally, the scale at which features were mapped was not consistent throughout their mapping product (Rodriguez Padilla, personal communication, March 8, 2022).

The mapping in these previous studies was, generally, limited to smaller areas and is less comprehensive than in this project, which involves mapping the entire rupture at a uniform scale.

Field Response Data Compilation

The data compilation from Ponti et al. (2020) serves as the main source for all ground deformation observations collected following the RES. The Ponti et al. (2020) dataset is a compilation of data acquired at various scales and levels of detail by dozens of geologists and other scientists. These data include: 1) more than 6,000 site-specific ground observations, ~1,500 of which merely document the presence or absence of ground deformation, with the remainder including quantitative measurements of displacement, detailed descriptions, and tens of thousands of photographs; and 2) surface rupture maps created in the field or interpreted from optical and geodetic imagery that may or may not have been verified in the field (Ponti et al., 2020).

METHODOLOGY

Our objective is to present mapping of both the M_w 6.4 and M_w 7.1 surface ruptures at a uniform scale utilizing lidar and orthoimagery derived from Hudnut et al. (2020). Our mapping relies primarily on the lidar, which we then supplemented with the orthoimagery. We used the lidar as the main data source because it is most uniform throughout the rupture area, whereas the optical imagery was simply co-collected, meaning the survey was not optimized for its collection.

Sources for Rupture Mapping

The initial field reconnaissance aided in defining area of interest (AOI) polygons for lidar and aerial photography collection (Hudnut et al., 2020) (Figure 2). The lidar and aerial photographs that serve as the source data for this mapping project were collected on August 2, 2019, by the National Center for Airborne Laser Mapping (NCALM), funded by the USGS and The National Science Foundation (Hudnut et al., 2020). The primary fault ruptures were surveyed at the highest resolution of 80 pulses per square meter (ppsm) (Figure 2). A larger surrounding area, which was collected at 25 ppsm, covers most of the secondary ruptures and ground cracks. In addition to lidar, overlapped, stereo aerial photographs were collected over the entire area covered by the AOI polygons. We chose to use the lidar and optical imagery datasets of Hudnut et al. (2020) for this project, as they offer the most uniform and extensive sources available.

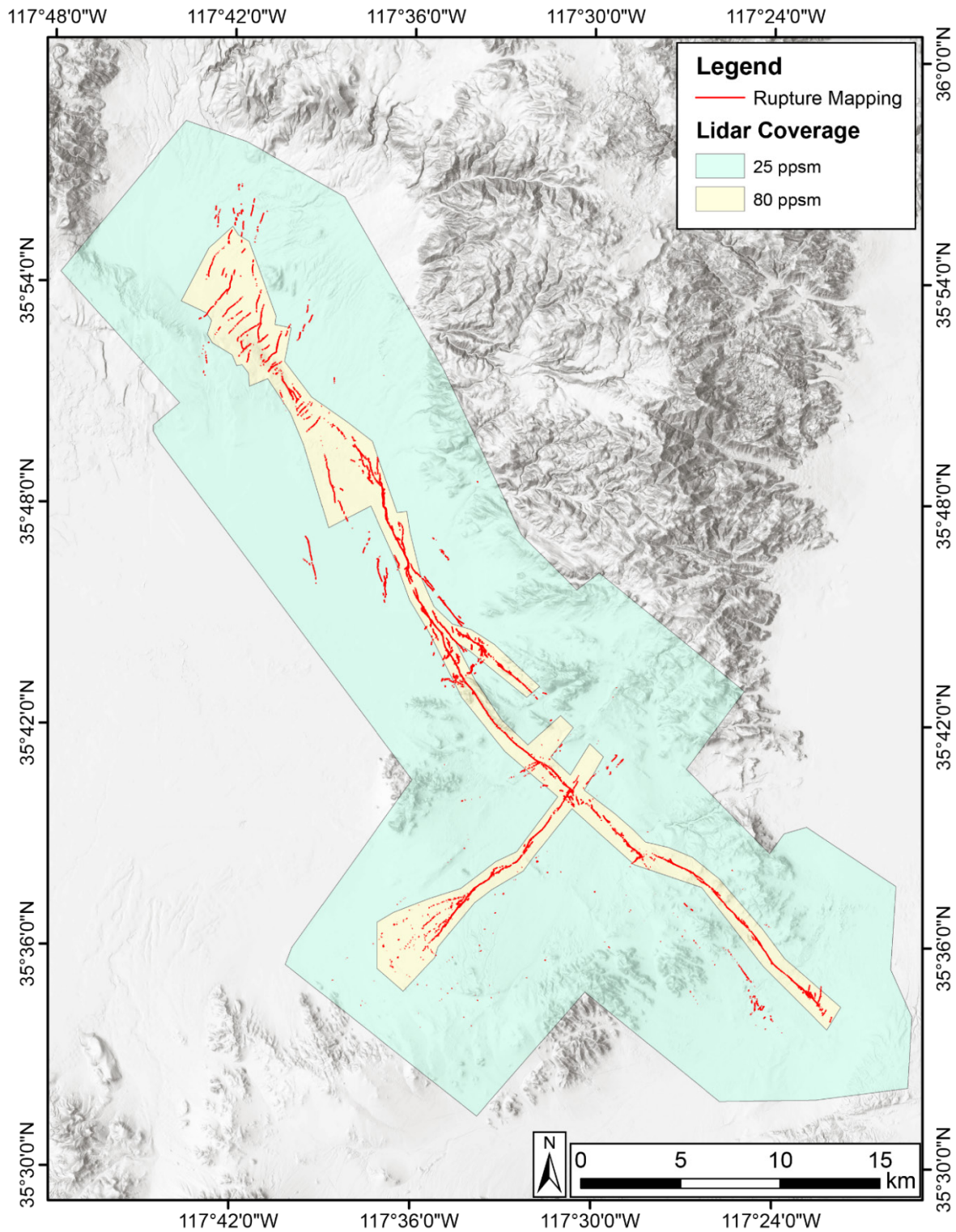


Figure 2. Lidar and orthoimagery coverages for project area. Red lines indicate surface ruptures mapped by this project. The green polygon portrays the entire extent of the orthoimagery acquisition and lidar that was collected at 25 pulses/m² in Hudnut et al. (2020). The yellow polygon represents the higher resolution lidar collected at 80 pulses/m² along primary surface ruptures. Base source: Airbus, USGS, NGA, NASA, CGIAR, NLS, OS, NMA, Geodatastyrelsen, GSA, GSI and the GIS User Community.

Lidar Derivatives Used

The mapping in this report utilizes standardized lidar derivative products such as 45°, 315°, and multi-directional hillshades (Figure 3). We performed geomorphic interpretation and mapping with lidar at a digital screen scale of 1:300 to 1:500, using a combination of the 45°, 315°, and multi-directional hillshades, depending on the area of interest and the visibility of surface ruptures and ground deformation.

The multi-directional hillshade is useful in this region due to the mostly low-lying desert environment. It combines light from six different directions, which enhances the terrain and improves the appearance of regions with low relief. The multi-directional hillshade also balances out overexposed and shadowed areas of the lidar, allowing for mapping to be done in areas where surface rupture and ground deformation features may not be visible in the other hillshade products. Given their broad utility, these three hillshade products are standard lidar derivatives that we would regularly use for earthquake rupture and ground deformation mapping projects.

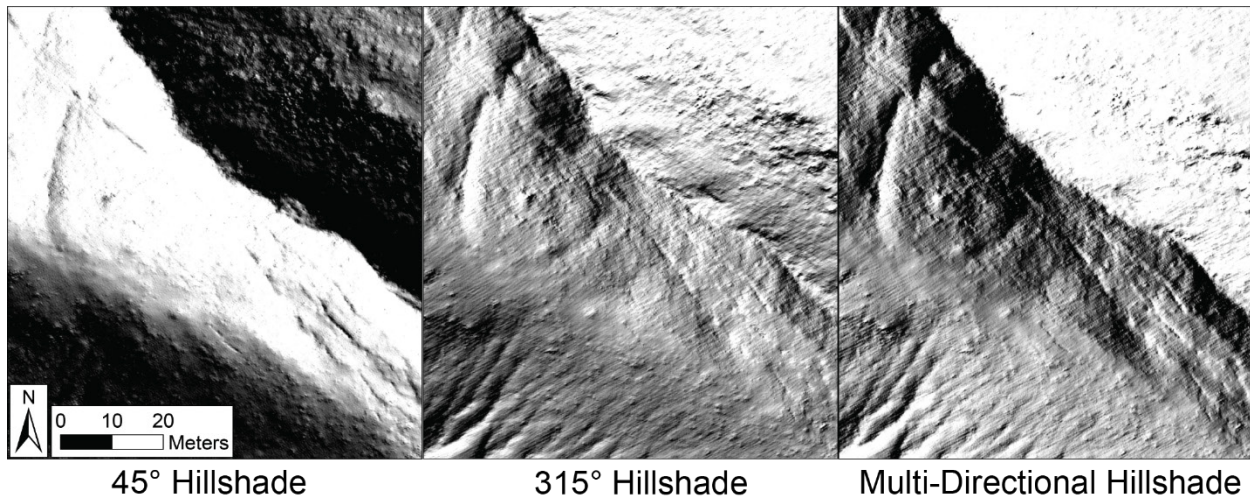


Figure 3. Examples of derivative lidar products used for remote mapping from the same view at 1:500 scale. From left to right: 45°, 315°, and multi-directional hillshades.

Orthoimagery

The aerial photographs co-collected during the lidar survey were orthorectified to create the orthoimagery product used in our mapping, with the final product having a ground sample distance of 5-10 cm (Hudnut et al., 2020). As noted above, optical imagery collection was not optimized during the lidar survey, so we used the orthoimagery dataset for supplemental linework mapping, especially in areas with minor displacements. While the majority of the orthoimagery is useful and provides good resolution, the quality of photos is not consistent: numerous photos are blurry, display issues with color, or have low contrast that make resolving features difficult. Regardless, the use of orthoimagery is valuable for validating features mapped from the lidar, especially in this region where washes, roads, and other cultural features sometimes align with verified surface fault rupture.

Mapping of Rupture on Lidar and Orthoimagery

The purpose of this project was for a small group of scientists (three maximum) to map the entire rupture at a consistent scale (1:300 to 1:500), aiming to improve upon existing rupture mapping products for the RES. At these scales and utilizing the different derivative imagery sources (lidar hillshades and orthophotographs) from Hudnut et al. (2020), we were able to map centimeter-scale fault features and minor cracking as well as the major ruptures. We distinguished features that are directly tectonic in origin (i.e., caused by fault displacement) from other earthquake-induced ground failure such as shaking-related ground fractures. We mapped the full lateral extent of the rupture zone, including primary faults and secondary, off-fault ground deformation, allowing for more qualitative descriptions of these features and an extensive catalog of attributes for both fault zones. We utilized narrowly defined criteria and guidelines to assess and categorize surface rupture features, producing a comprehensive and spatially consistent dataset that covers the entire lidar and orthoimagery bases (see Table 1). We generalized attributes with regard to fault zone labeling, especially in the vicinity where the fault zones intersect: in that region, northwest-southeast trending features were labeled as the Paxton Ranch Fault Zone, and northeast-southwest trending features were labeled as the Salt Wells Valley Fault Zone.

Process

We initially mapped on the lidar and subsequently utilized the orthoimagery to ensure all visible features, including features with minimal to no vertical displacement, were captured, especially those closest to the primary ruptures. Additionally, the orthoimagery was sometimes used to verify the attribute confidence for the feature. Of note, orthoimagery coverage does not exist in all areas where there is lidar coverage, and vice versa. In some areas of complex fracturing, the mapping is generalized to capture the area, but not necessarily every detail of the surface ruptures.

As noted above, this mapping dataset includes a catalog to categorize attributes of the mapped features (Table 1). All lines are classified by type (fault, lineament, or fracture) and confidence in existence and identity. As features are mapped on lidar and optical orthoimagery, default existence confidence is high unless there is some indication the feature could be a scan artifact. Identity confidence is related to the line type: features classified as “certain” determined using observations and scientific judgement; “questionable” features have a lower confidence in interpretation and typically associated with lineaments, fractures, and/or pre-existing features. Features are assigned to a fault zone (Paxton Ranch or Salt Wells Valley Fault Zone) and data source (lidar or orthoimagery) (see Table 1 for definitions). Additionally for each feature, if there is a vertical component of slip (e.g., a scarp), this is preserved in our table along with the scarp facing direction. Text descriptions are included if necessary to further describe the mapped feature.

Table 1. Schema and explanations for mapping and cataloging surface rupture features

Attribute	Field Values and Definitions
Type	Lidar-based mapping: Faults are features clearly identifiable as surface ruptures and typically have vertical relief. Lineaments are linear features that are mappable but have greater origin uncertainty. Examples might include geologic contacts and geomorphic features, such as channel margins, where the geologist cannot determine if the linear feature ruptured during the earthquake. Fractures are not typically assigned when interpreting lidar data, because these features lack vertical relief or are typically below the resolution of lidar to resolve but are visible on optical imagery. Imagery-based mapping: Faults meets the same criteria as described above for lidar-based mapping. The geologist may also use other criteria such as en echelon stepping patterns of rupture to assign the features as faults. Lineaments are the same as described above. Fractures are mappable cracks where it is uncertain if there is displacement (other than an opening mode).
ExistenceConfidence	The surface rupture and ground deformation mapping are on lidar and optical orthoimagery, so default confidence is high and assigned as “ certain ”. If there is some indication the feature could be a scan artifact (e.g., lidar “corduroy”), linework is assigned as “ questionable ”.
IdentityConfidence	This field is related to the “Type” field. Certain: Identity of feature can be determined using relevant observations and scientific judgement. Questionable: Identity of feature cannot be determined using relevant observations and scientific judgement. There is low confidence in the credibility of this interpretation and will typically be associated with lineaments and fractures and/or pre-existing features.
Scarp	Used to indicate if fault rupture has a vertical component of slip (either real or apparent) and denoted by a “Y” or “N”
ScarpFacingDirection	One of the eight cardinal/ordinal directions (e.g., N, NE, E, SE, S, SW, W, NW)
Label	Feature associated with the Paxton Ranch Fault Zone or the Salt Wells Valley Fault Zone. This attribute is generalized and not intended to assign origin of a feature to an event.
InterpretationSourceID	Basemap upon which features were mapped. NCALM Lidar dataset or NCALM orthoimagery (Hudnut et al., 2020)
Notes	Text for additional information and descriptions specific to the mapped feature.

Lidar and Orthoimagery Resolution

The lidar resolution allows us to map primary rupture and secondary ground deformation features with greater accuracy than what has been previously published along the full extent of the rupture zone. While lidar artifacts (e.g., scan artifacts, such as lidar “corduroy”) are present in the dataset, mapping at a 1:500 scale provides an acceptable balance between the ability to resolve surface rupture features without having an overabundance of artifacts (Figure 4).

Not all features are captured in both the lidar and orthoimagery datasets. Some features that are easily mappable on the lidar are not visible on the orthoimagery (Figure 5). This is likely due to poor photo quality as discussed earlier. At other locations, surface rupture and other ground deformation features visible on the orthoimagery, such as ground cracks with little to no vertical offset, are not visible on the lidar, or lidar artifacts interfere with their expression, reducing location accuracy in mapping (Figure 6).

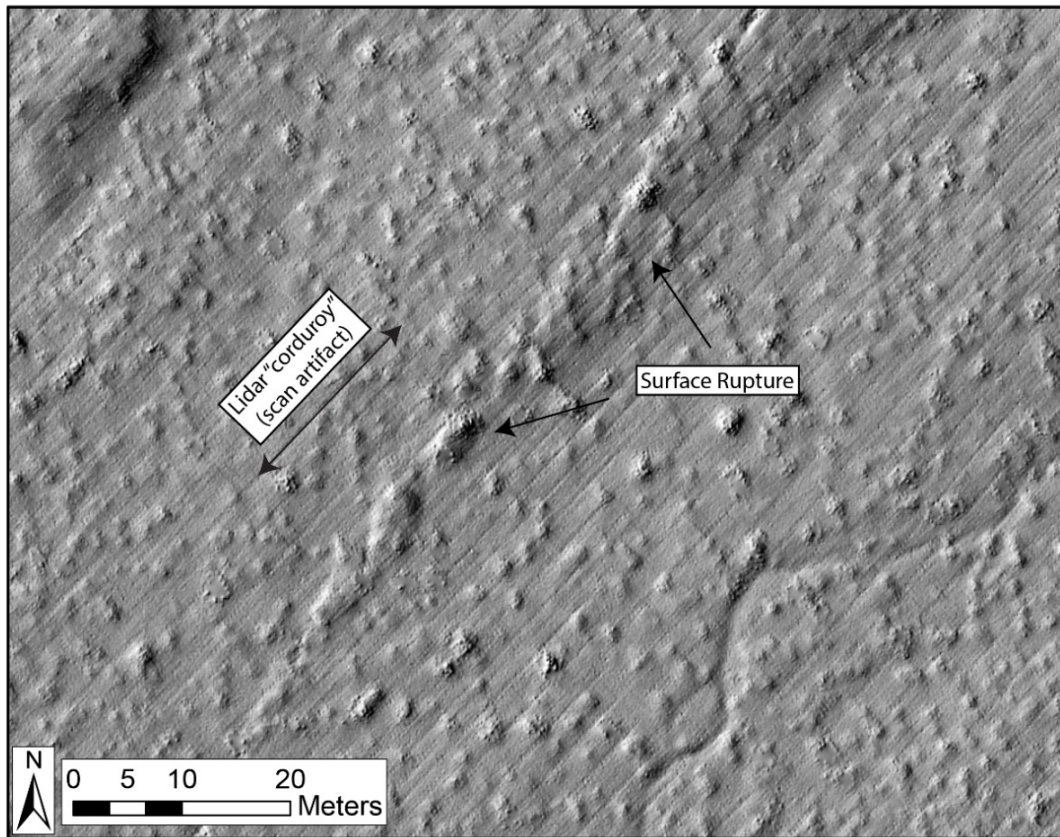


Figure 4. Example of scan artifacts visible in lidar (i.e., lidar “corduroy”) at 1:500 scale that are present in the Hudnut *et al.* (2020) dataset. Scan artifacts can have a similar trend to surface rupture (noted on figure with black arrows) that can make resolving tectonic features difficult. Base is the multi-directional hillshade.

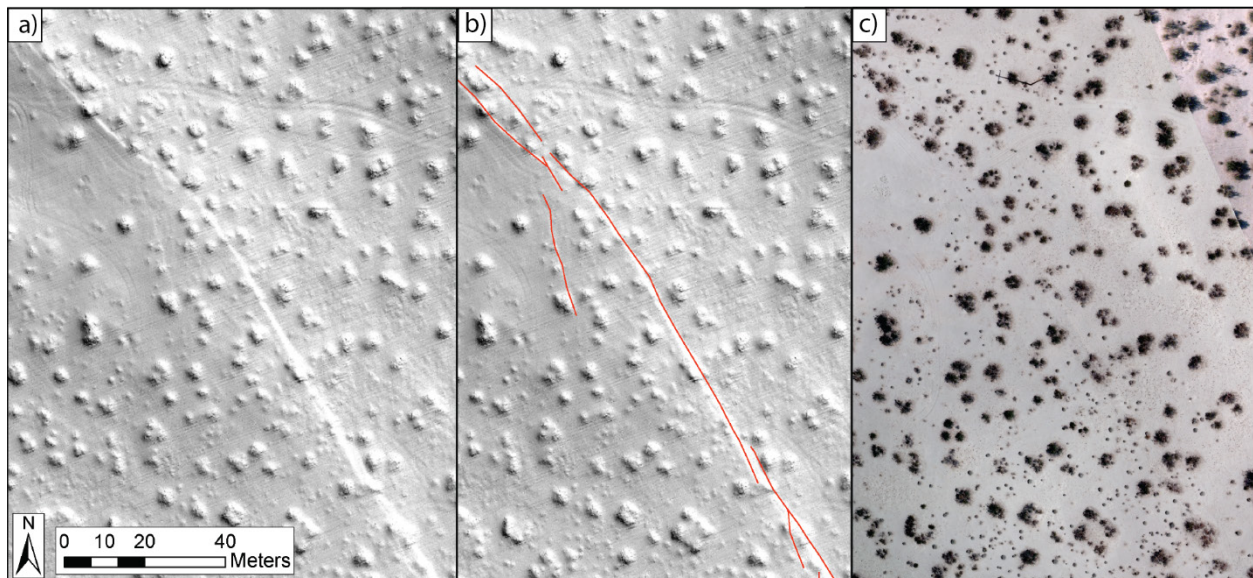


Figure 5. Images depicting visibility of surface rupture features in lidar but not in orthoimagery for the same location (shown at 1:1,200 scale). At this location, it could be due to the photo contrast being too low to see the surface rupture features. a) northwest-southeast striking unmapped features in lidar; b) same image as a), but with surface rupture features mapped in red; c) orthoimagery image in same location as a) and b), but no features are visible. Base is the 45-degree hillshade for a) and b), and orthoimagery for c).

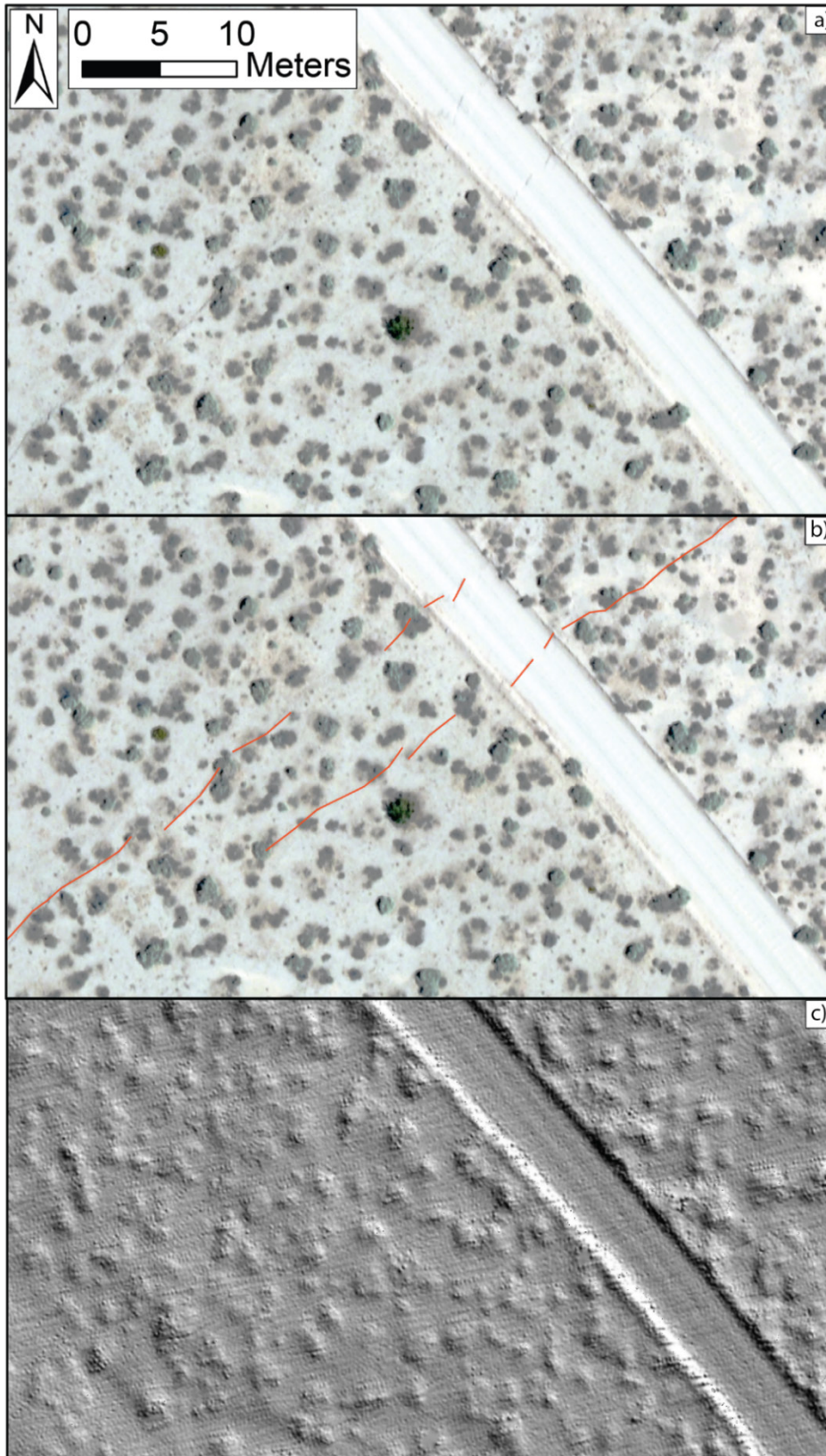


Figure 6. Images depicting visibility of surface rupture features in orthoimagery but not in lidar for the same location (at 1:400 scale). At this location, the lack of surface rupture visibility in the lidar is likely due to little or no vertical offset. a) orthophoto of rupture zone; b) same image as a), but with surface rupture features mapped in red; c) lidar image in same location as a) and b), but no features visible. Base is the orthoimagery for a) and b) and 45-degree hillshade for c).

CHARACTERIZATION OF SURFACE RUPTURE AND GROUND DEFORMATION

Both fault zones encompass primary faults expressed as throughgoing linear cracks, distributed fractures, and scarps (Figure 7), with localized contractional and extensional deformational features. Contractional features include moletracks and push-ups, with extensional features expressed as depressions (such as troughs and pull-aparts) and grabens (Figure 8).

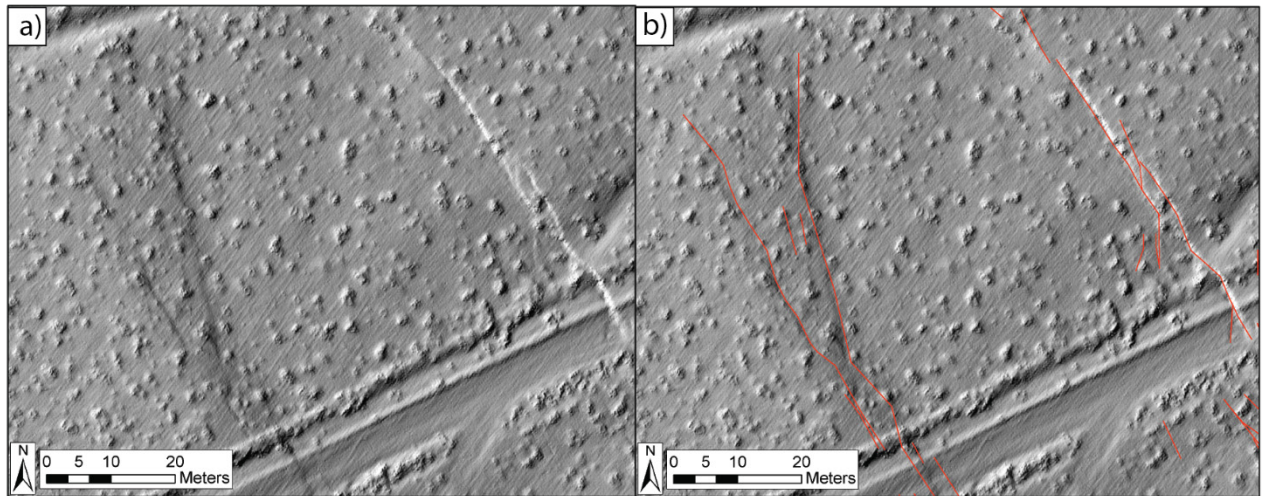


Figure 7. Example of appearance of both east- and west-facing scarps in lidar at 1:700 scale. a) shows features without corresponding mapping; b) shows mapping of features in red. Base is the multi-directional hillshade.

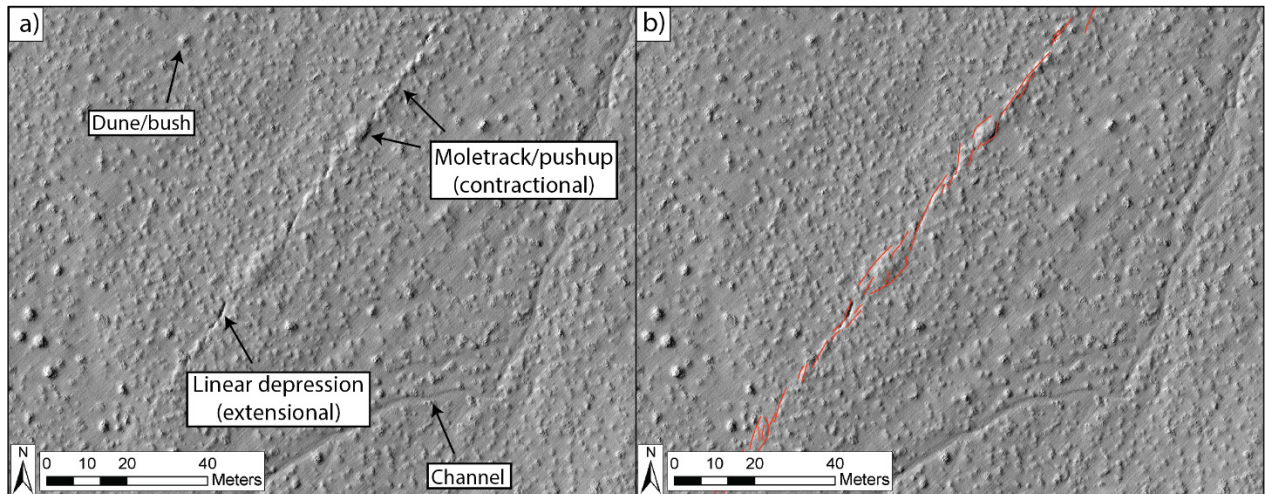


Figure 8. Depiction of surface rupture expression in lidar appearing as extensional (e.g., linear depressions) and contractional features (e.g., moletracks and pushups) at 1:1,000 scale. Additionally shown are natural features such as channels, dunes, and bushes. a) shows features labeled without corresponding mapping; b) shows mapping of features in red. Base is the multi-directional hillshade.

In bedrock, surface rupture appears more constrained into discrete, linear fault strands (Figure 9) and is widely distributed with large separations through unconsolidated, soft sediments of playa areas (Figure 10). The rupture produced scarps as high as about 3 m, which can be readily delineated from the lidar (Figure 11), with narrow, well-defined scarps that have large vertical displacements most easily recognizable. Where the fault zone and scarp become wider, it is more difficult to detect a discrete rupture trace (Figure 12).

Secondary ground deformation features include zones of discontinuous and distributed cracks off the main faults and fractures with little to no vertical offset that cannot be seen in lidar but can be recognized in the orthoimagery (e.g., Figure 6). We mapped small fractures and lineaments, identified in both the lidar and orthoimagery, as far as 3-4 km from the primary fault strands. We interpret most of these features to be the product of ground-shaking rather than being tectonic in origin.

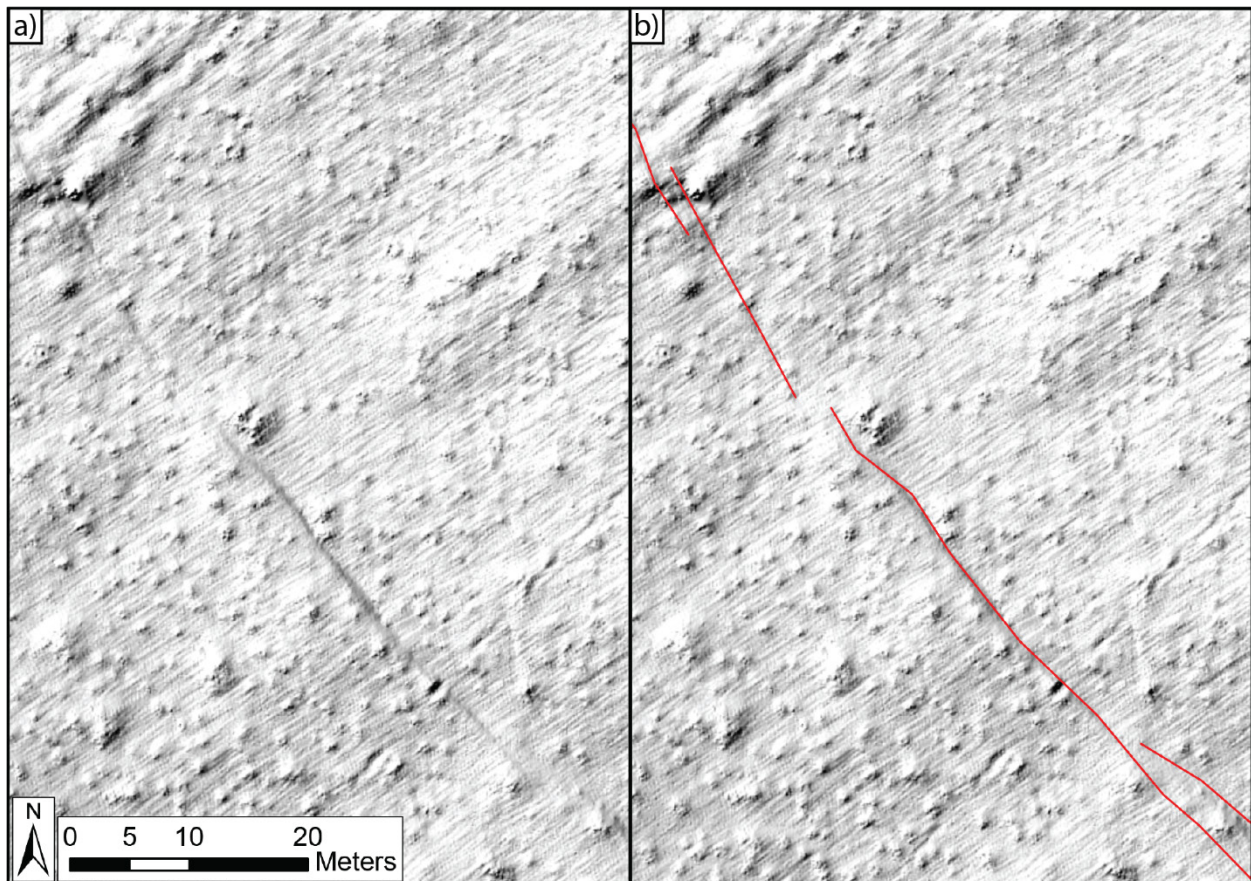


Figure 9. Appearance of faulting through bedrock at 1:500 scale. a) shows features without corresponding mapping; b) shows mapping of features in red. Base is the multi-directional hillshade.

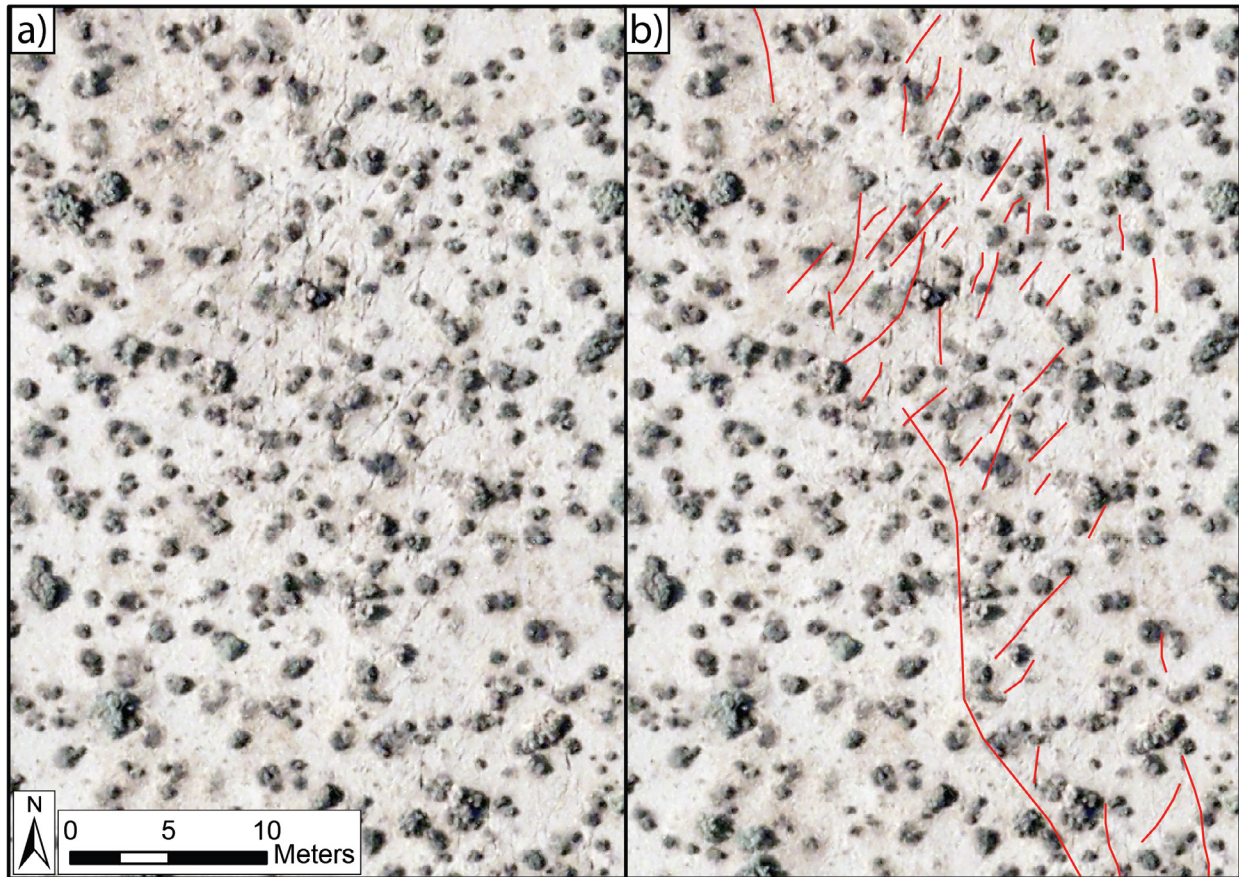


Figure 10. Appearance of diffuse faulting in unconsolidated playa areas at 1:300 scale. a) shows features without corresponding mapping; b) shows mapping of features in red. Base is the orthoimagery.

Our mapping captured ~16 km of mostly continuous rupture attributed to the M_w 6.4 foreshock and ~50 km of total surface rupture length attributed to the M_w 7.1 mainshock (Figure 1). The rupture patterns for both events are primarily expressed as continuous primary fault strands with many short and discontinuous subparallel fault strands. Both the southwestern terminus of the M_w 6.4 rupture and the southeastern terminus of the M_w 7.1 rupture are characterized by primary rupture strands that splay into discontinuous fault traces, creating 2.5-km- and 2-km-wide rupture zones, respectively. At the southern and northern termini of the M_w 7.1 rupture, there are numerous northeast-southwest striking left-stepping faults, one to two kilometers in length. Additionally, two short, northeast-southwest trending zones of discontinuous faulting are mapped north and south of the intersection of both ruptures.

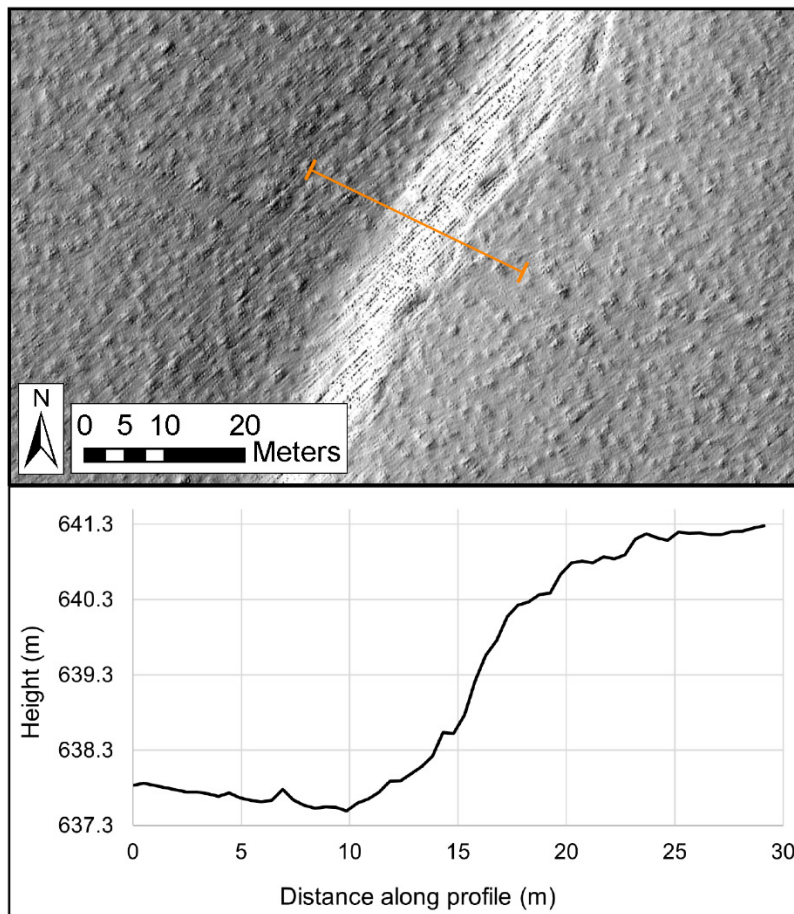
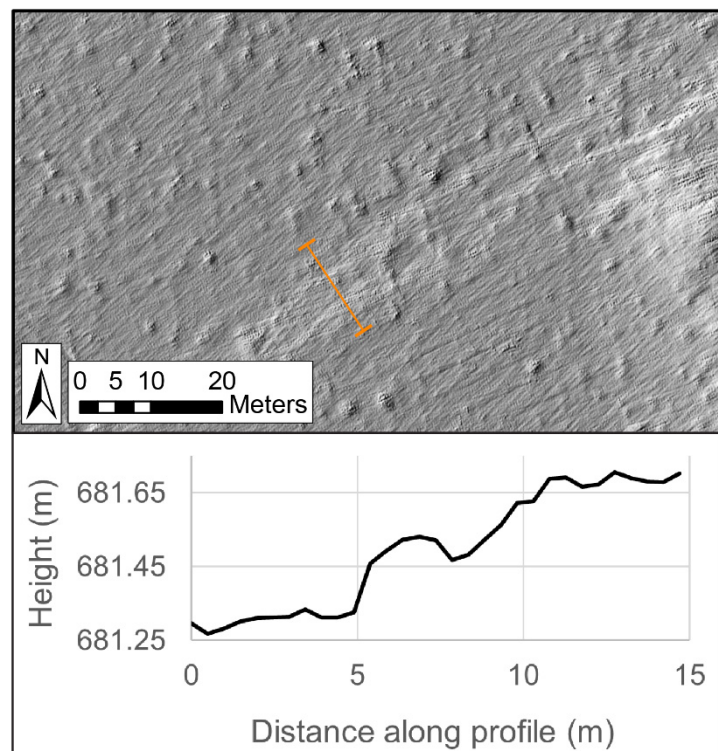


Figure 11. Example of distinct scarp in narrow rupture zone (top image) and profile (orange line) across zone. Profile graph (bottom image) shows height in meters (y-axis) relative to distance along profile in meters (x-axis). This scarp is 3 m high and can be easily delineated from the lidar at this location. Base is multidirectional hillshade.

Figure 12. Example of a distributed rupture zone (top image), where a discrete scarp is difficult to detect. Profile graph (bottom image; profile location depicted by orange line above) shows height in meters (y-axis) relative to distance along profile in meters (x-axis). This specific profile graph shows that distinct scarps in distributed rupture zones are difficult to detect. Base is multidirectional hillshade.



COMPARISON WITH PREVIOUS MAPPING

The surface rupture mapping dataset from this project differs from the previously published maps discussed earlier in several aspects. As noted earlier, some of the prior mapping does not cover the entire extent of both earthquakes' surface rupture, and the goals of these projects may differ from that of ours. We selected two of these other mapping efforts, Ponti et al. (2020) and Pierce et al. (2020), for a detailed comparison with this dataset, to illustrate how it is distinct from others produced after the earthquakes. Pierce et al. (2020) only targeted the southern terminus of the M_w 7.1 rupture, using high-resolution aerial photos collected in a drone survey. The Ponti et al. (2020) dataset, the most comprehensive of the previously published rupture maps, was compiled from a mix of data sources incorporating various methods, resolutions, and scales.

Comparison with Mapping by Ponti et al. (2020)

The Ponti et al. (2020) dataset is a compilation of site-specific, on-the-ground observations of rupture traces and rupture-related ground deformation (e.g., scarps, cracks, offset features, etc.) acquired in the immediate aftermath of the RES. These observations also include quantitative measurements of displacements, descriptions of rupture characteristics, and photographs.

In addition to field observations, the dataset includes ruptures mapped with remote sensing techniques, not all of which were completely documented or verified in the field. The Ponti et al. (2020) dataset integrated field-based maps with interpretations derived from post-earthquake airborne imagery, lidar, and geodetic imagery products. Ponti et al. (2020) used several kinds of satellite and radar imagery (e.g., optical and radar satellite imagery, lineament maps from correlation of pre- and post-earthquake imagery, etc.) to identify and interpret the presence of surface rupture. Fault rupture mapped directly in the field was done by walking along features with handheld and survey-grade GPS/GNSS (Global Positioning System/Global Navigation Satellite Systems) receivers, and tablets and cellphones with applications for data collection using device GPS (Ponti et al., 2020). Additionally, rupture linework included in the Ponti et al. (2020) dataset was produced by connecting waypoints collected using handheld devices (e.g., GPS/GNSS receivers, tablets, cellphones, etc.), resulting in a significant portion of the linework interpolated between site-specific observations and waypoints, rather than explicitly mapped in the field. Linework was also interpreted from high-resolution imagery (e.g., aerial imagery and digital surface models obtained with Unmanned Aerial Vehicles, or UAVs). As such, surface rupture mapping within Ponti et al. (2020) is of varying levels of detail and location accuracy. As discussed in Ponti et al. (2020), horizontal accuracy can vary between 2.5 to more than 200 m depending on device type, network provider, satellite geometry, and local conditions, and they conclude the accuracy of most observations in their dataset is on the order of 10 m or less, but locations uncertainties as high as several hundred meters were noted. Ponti et al. (2020) discuss within their report that, while surface ruptures mapped using survey-grade GNSS instruments have a 3-20 cm horizontal location accuracy, linework derived from cellphones, tablets, or handheld GPS devices have location accuracies that vary between 2.5-10 m and tend to not preserve fine-scale expression of surface ruptures. Linework produced with aerial, satellite, or geodetic imagery products is done manually and at varying scales, with resolutions that are dependent on the base imagery. Whereas resolutions of UAV-collected imagery vary between 1 and 10 cm ground sample distance and allows for fine-scale mapping, imagery collected with

satellites and geodetic image products range from 0.3 m to several meters and fine-scale rupture details are generally not observable (Ponti et al., 2020).

Our mapping has captured many of the same features as that of Ponti et al. (2020), excluding the slip measurements. However, when comparing our mapping with that of Ponti et al. (2020), it is apparent there are discrepancies in location, detail, continuity, and extent of surface rupture and ground deformation features. For example, lateral distances between our linework and that of Ponti et al. (2020) can be as large as 10 m (Figure 13), likely due to the Ponti et al. (2020) rupture linework in that area being mapped on imagery with 0.5 to 3 m resolutions.

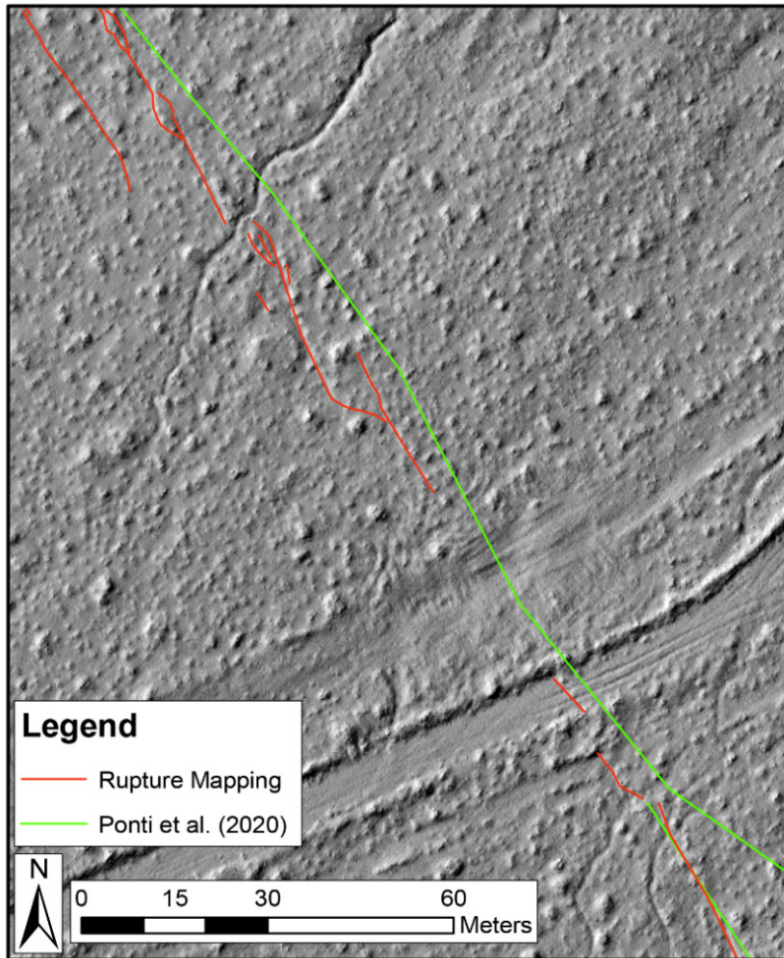


Figure 13. Comparison of our rupture mapping with Ponti et al. (2020) showing variation in locations of rupture features at 1:600 scale. Data source for Ponti et al. (2020) linework in this specific location is a mix of imagery and remote sensing with resolutions ranging from 0.5 to 3 m mapped remotely. This figure shows an example of how the difference between the locations of rupture features in these two datasets can be up to 10 m, likely due to the variations in the source resolution for the Ponti et al. (2020) linework. This figure is also an example of how these two datasets capture the fine-scale features of the rupture differently. Specifically, at this location, our mapping has captured more detail in the rupture's expression, versus the simplified linework of Ponti et al. (2020). Base is the multi-directional hillshade.

Another result of lower resolution sources for rupture linework in Ponti et al. (2020) is that, in places, their mapping is simplified relative to our dataset which has more fine-scale detail of the rupture (Figure 14). Elsewhere, our mapping on a higher-resolution source imagery captured surface rupture that Ponti et al. (2020) did not document (Figure 15).

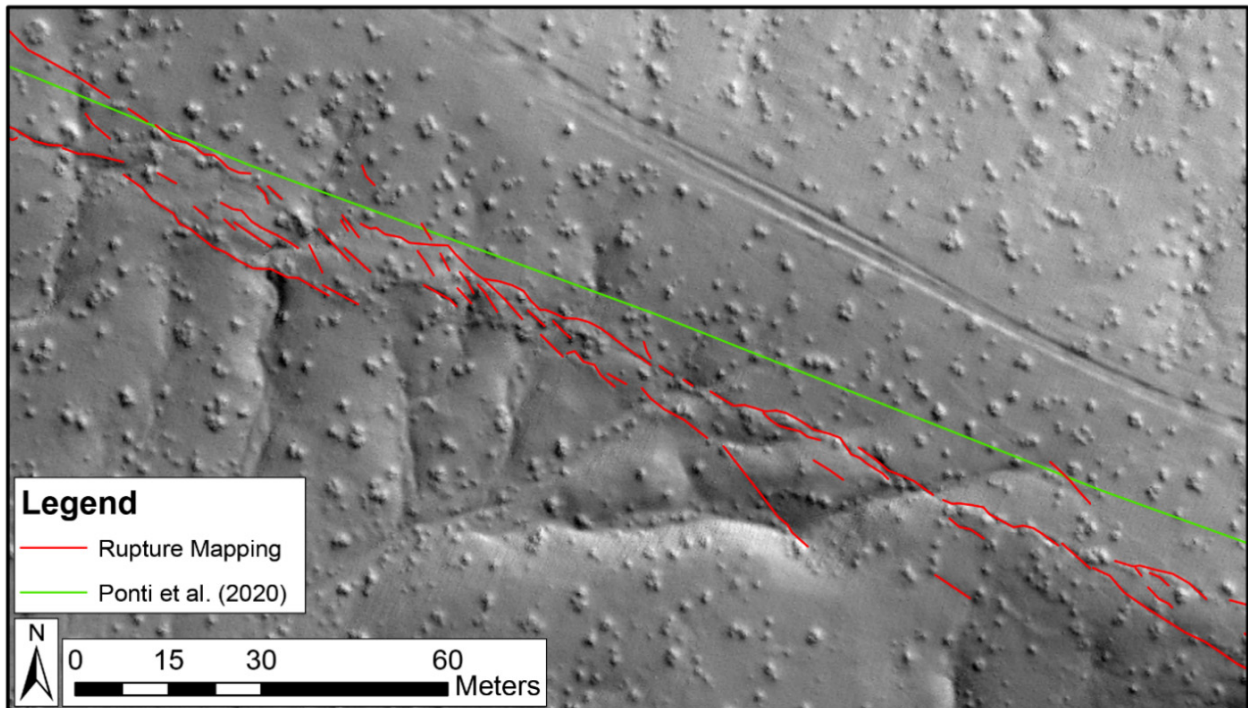


Figure 14. Comparison of our rupture mapping with Ponti et al. (2020) showing difference in capturing rupture's expression at 1:1,000 scale. Data source for Ponti et al. (2020) linework in this specific location is imagery with 0.5 m resolution mapped remotely. This figure shows an example of how these two datasets capture the rupture's expression differently. Specifically, at this location, our mapping has captured more detail in the fine-scale expression of the rupture, versus the simplified linework of Ponti et al. (2020). This is likely due to the lower resolution of the Ponti et al. (2020) linework at this location, which makes mapping of finer-scale features difficult. Base is the 45-degree hillshade.

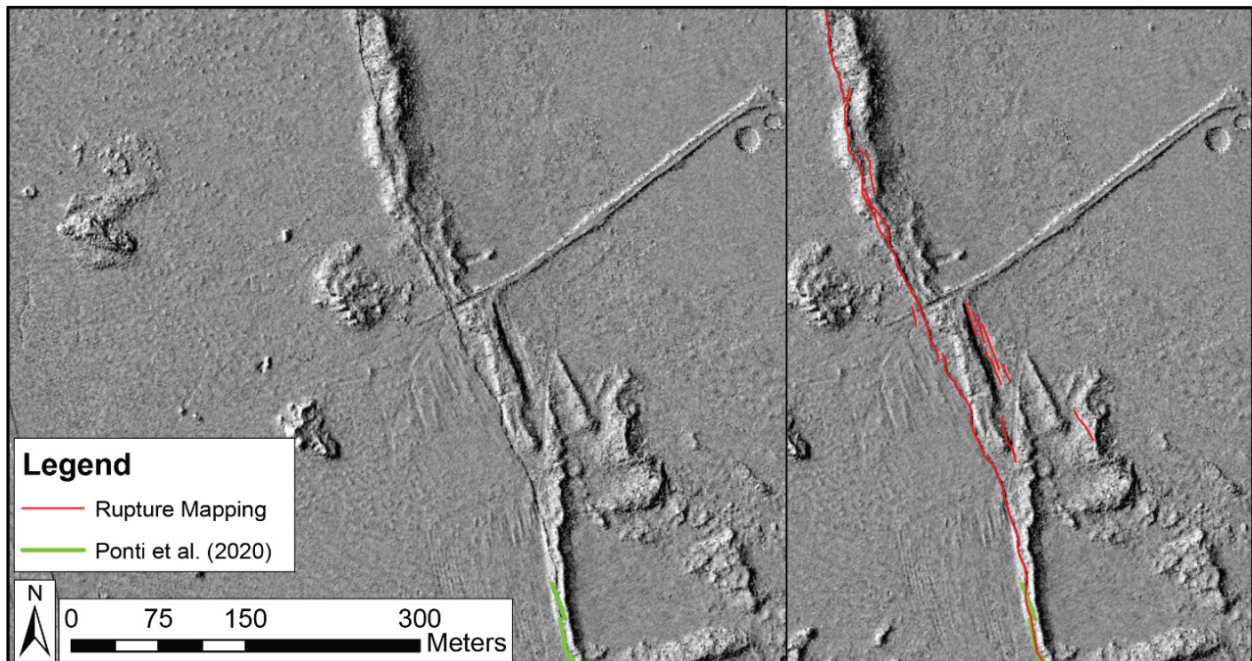


Figure 15. Comparison of our rupture mapping with Ponti et al. (2020) showing previously undocumented surface rupture captured in our dataset at 1:5,000 scale. Data source for Ponti et al. (2020) linework in this specific location is from: 1) field mapping using a GPS/GNSS device; and 2) imagery with 3 m resolution mapped remotely. Left image shows location with only mapping from Ponti et al. (2020) in bottom of image and right image shows mapping from both our dataset and that of Ponti et al. (2020). This figure shows an example area where surface rupture that was previously undocumented in the Ponti et al. (2020) dataset is captured in our dataset. This could be due to a lack of time in the field to explore this portion of the rupture further. Base is the multi-directional hillshade.

There are several reasons why our dataset includes features that Ponti et al. (2020) did not map, such as: 1) a lack of time in the field to explore the rupture further; or 2) the mapping from the Ponti et al. (2020) dataset in a specific area comes from non-ground-based observations of a lower resolution, which results in simplified linework. There are areas where our mapped ruptures are more discontinuous than those in the Ponti et al. (2020) dataset. For example, many of the small fractures and lineaments mapped in our dataset as far as 3-4 km from the primary fault strands correspond with linework from Ponti et al. (2020), but we were not able to capture as much continuity. This is especially evident in the northeast-southwest trending zone of discontinuous faulting approximately 2.5 km northwest of the main M_w 6.4 rupture, where the Ponti et al. (2020) dataset has an additional ~3.5 km of mapping west of the M_w 7.1 rupture (Figure 16). This may be due to either: 1) features being too small to resolve in our mapping; or 2) because of the inferred nature of the linework from Ponti et al. (2020).

Comparison with Mapping by Pierce et al. (2020)

Pierce et al. (2020) presented a map of surface ruptures along ~12 km of the southeastern terminus of the M_w 7.1 event utilizing aerial photographs collected with low-flying drones. These images were collected at ~30 - 60 m above ground and provide a high-resolution imagery dataset with resolutions ranging from ~1 - 20 cm/pixel (Pierce et al., 2020). Their surface rupture mapping, at a variable scale between 1:40 and 1:150, shows a distinct moletrack, left-stepping en echelon faults, and numerous subparallel cracks (Pierce et al., 2020). When comparing our mapping to that of Pierce et al. (2020), it is apparent that our mapping captures most of the same general pattern and extent of the surface ruptures but does not capture all the fine-scale rupture features. For example, in Figure 17, areas with distributed rupture expressed primarily as short cracks are visible on the low altitude orthophotos and mapped in Pierce et al. (2020) but were not captured in our dataset. These differences are expected as: 1) we mapped at a smaller scale making subtle features more difficult to delineate; and/or 2) features may not be visible on the lower quality photos we used.

The Pierce et al. (2020) dataset demonstrates how low-altitude images are especially useful for detailed large-scale post-earthquake surface rupture mapping. While large-scale mapping on low-altitude high-resolution orthoimagery seems to be best for documenting surface ruptures in terms of detail and completeness, the time required suggests that this approach is most appropriate for site-specific study questions that require a high level of detail but a small coverage area. This type of mapping may not be reasonable as a default rupture mapping approach for large areas and geographically extensive fault ruptures. Our dataset and that of Pierce et al. (2020) captured the same general pattern and extent of surface ruptures of southeastern terminus of the M_w 7.1 event. However, with each study having a different focus and mapping approach, evident with the abundance of fine-scale features documented in Pierce et al. (2020) that are not in our dataset, it is apparent that these two datasets complement rather than substitute for each other.

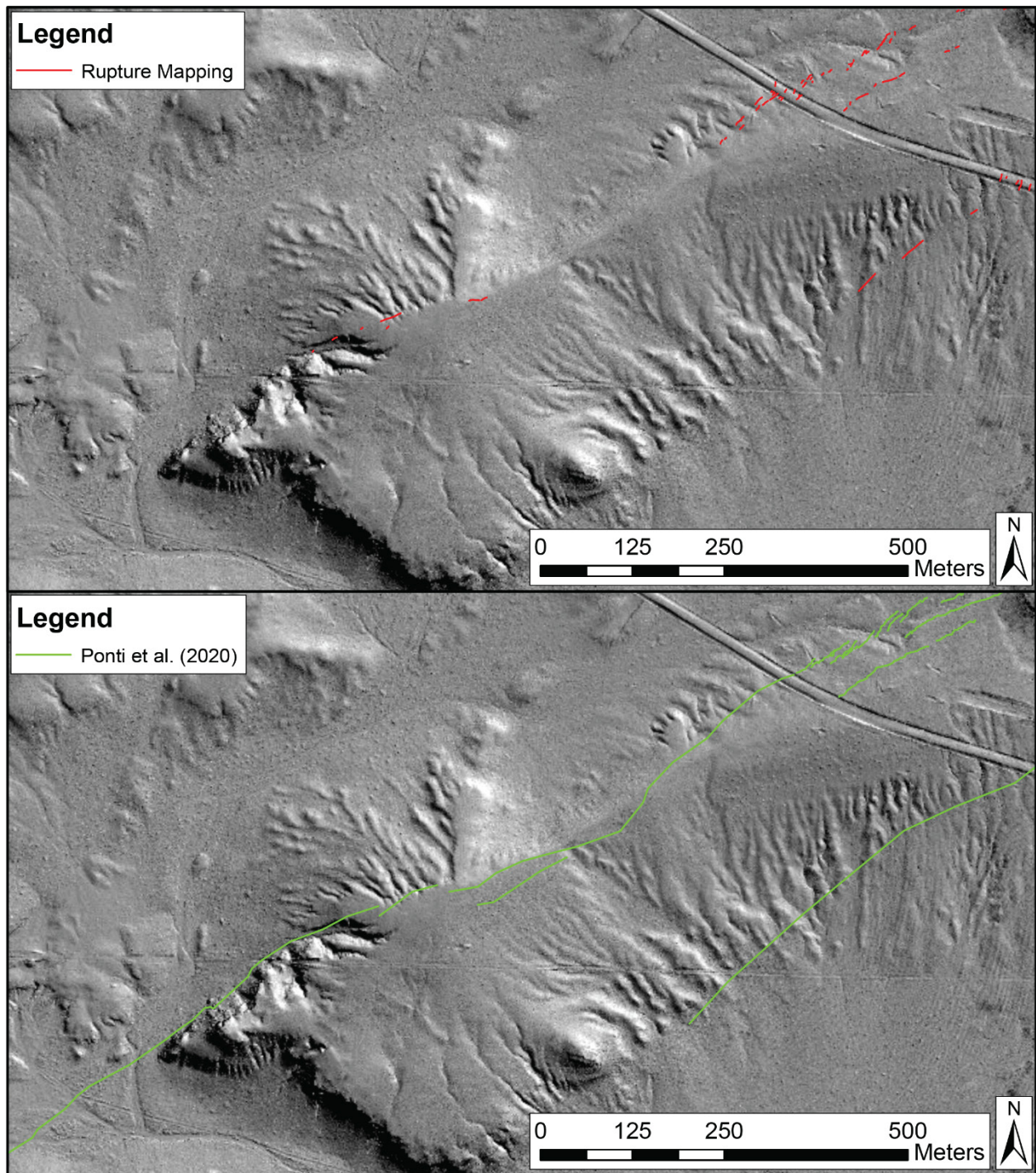


Figure 16. Image showing where our rupture mapping lacks continuity and shorter extent when compared with Ponti et al. (2020) at 1:7,000 scale. Data source for Ponti et al. (2020) linework in this specific location comes from: 1) linework inferred from waypoints; and 2) field mapping using a GPS/GNSS device. This figure shows an example area where our mapping of the surface rupture has a lack of continuity and shorter extent when compared with the Ponti et al. (2020) dataset. Many of the small fractures and lineaments mapped in our dataset appear to correspond with linework from Ponti et al. (2020), but we are not able to capture as much continuity. This may be due to either features being too small to resolve at the scale we are mapping and/or because of the inferred nature of the linework from Ponti et al. (2020). Base is the 45-degree hillshade.

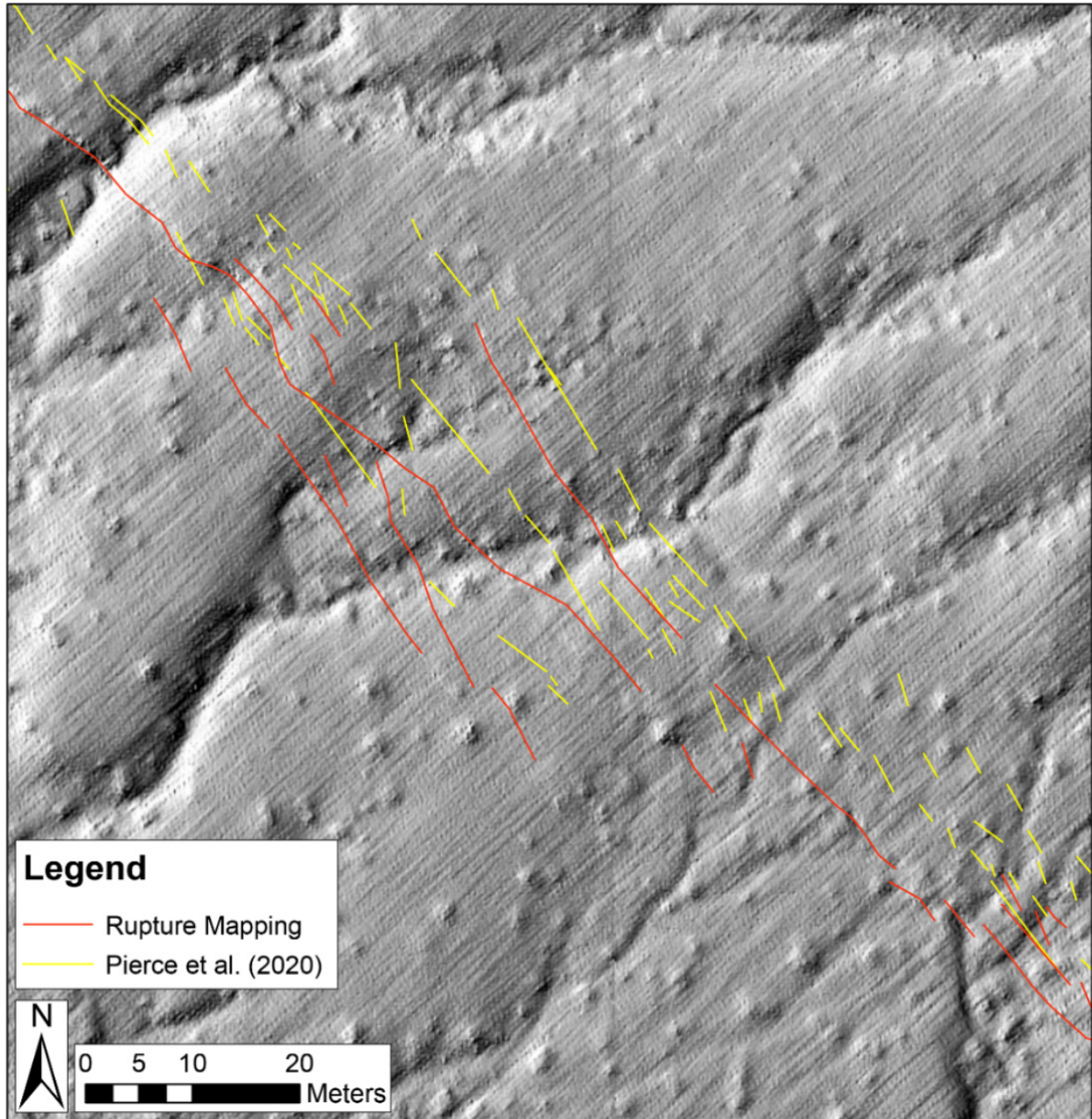


Figure 17. Comparison of our rupture mapping with Pierce et al. (2020). The difference in locations between our mapping and that of Pierce et al. (2020) may be due to errors in registration of the Pierce et al. (2020) dataset. Base is the multi-directional hillshade.

SUMMARY

The lidar and orthoimagery used in this project comprise, thus far, one of the highest-resolution, spatially extensive datasets acquired for post-earthquake rupture mapping for a historical earthquake. Many subtle surface rupture features captured within the imagery may not be preserved following weather events, making imagery collection time sensitive. The collection of both lidar and imagery is important following ground-rupturing earthquakes, as each type of data has unique advantages. Surface rupture and ground deformation features can often be

documented with greater location accuracy and detail using the paired lidar and imagery data than a single dataset. These datasets allowed us to map surface rupture and ground deformation features along the entire rupture extent of both events with high location accuracy. We documented visible features with qualitative descriptions and created an extensive catalog of attributes for both fault zones. Both fault zones comprise primary faults with throughgoing linear cracks, en echelon fractures, and scarps as high as 2-4 m, as well as extensional and contractional features along trend and off-fault secondary ground deformation features.

We found that high-resolution lidar imagery easily captures well-defined ruptures with at least 20 cm of vertical displacement. In areas where the deformation zone is broad, features are commonly less well-expressed, but in many cases are still identifiable. Utilizing orthoimagery is necessary for identifying rupture traces with little vertical offset and those that are expressed primarily as zones of distributed fractures. The orthoimagery in the Hudnut et al. (2020) dataset is of variable quality, with some blurriness and less than ideal lighting conditions, because it was co-collected with the lidar, and the survey was optimized for lidar, not imagery, collection. Nevertheless, we find that ruptures can be typically resolved at scales of 1:300 or larger. The orthoimagery is especially valuable for zones with distributed rupture and minimal displacement on any given trace. It is also useful for verifying deformation recorded using other techniques. Although mapping on the orthoimagery is possible at scales larger than 1:300, considerations such as the area involved and required person-hours may make such detailed mapping impractical.

When comparing our dataset with others compiled after the RES, we note that we mapped at a uniform scale with a dataset of uniform resolution (i.e., Hudnut et al., 2020) across the entire rupture zone, whereas other mapping datasets were of limited extent and/or of variable resolution. The Ponti et al. (2020) dataset was of variable resolution and based on a collection of different input data, not all of which was available for the entire rupture region. We were able to identify deformation in some places that Ponti et al. (2020) did not map, and in areas where Ponti et al. (2020) had relatively low-resolution data or limited coverage, and their resulting mapping was commonly more simplified than that in this dataset. In other places, Ponti et al. (2020) captured rupture more thoroughly with the combined breadth of geodetic and ground-based observations of their dataset. Pierce et al., 2020, using low-altitude orthophotos, mapped at a larger scale than our mapping (e.g.), and were able to identify more fine-scale features in these distributed zones than were visible to us. However, considering the large-scale necessary to map extensive, distributed fault ruptures, as Pierce et al. (2020) have done, that approach may not be practical for standard post-earthquake response rupture mapping over a large region. Clearly, there are trade-offs regarding the available person hours for mapping, as well as the base footprint, when choosing a mapping source. As such, our surface rupture mapping dataset is complementary to previous work.

This investigation of the RES ruptures demonstrates the utility for detailed mapping of coseismic earthquake rupture using uniform high-resolution topographic and imagery data collected immediately post-event. Mapping can be completed across an entire rupture zone with high and uniform location accuracy. The broad extent permits identifying areas of deformation that have not been documented in the field. Characterizing zones of deformation benefits from a paired approach using both high-resolution lidar and orthoimagery in addition to established ground-based collection methods. Our dataset of surface rupture features will be potentially useful for

longer term, geomorphic-based fault evaluation and studies of rupture patterns for $>M_w$ 6.0 earthquakes within the ECSZ. Earthquake ruptures are the primary evidence of large $>M_w$ 6.0 earthquakes and documenting observations from these events is important for better understanding of fault mechanics, fault displacement, and seismic hazard and risk assessment for life-safety and property.

DATA AND RESOURCES

Plates of the rupture mapping are included in the Appendix at 1:12,000 scale using the multidirectional hillshade (discussed within the report) as the basemap. Areas of no data on the base imagery are redacted due to the presence of the Naval Air Weapons Station China Lake. These plates do not encompass every mapped feature but are intended to give an overview of the rupture mapping, focusing on primary strands. More detailed linework and the associated catalog of attributes from this project's mapping is available as a feature service here: https://gis.conservation.ca.gov/server/rest/services/CGS/2019_Ridgecrest_Earthquakes_Rupture_Mapping/FeatureServer. The lidar and aerial photography from Hudnut et al. (2020) are available at: <https://doi.org/10.5069/G9W0942Z> and <https://hddsexplorer.usgs.gov/>, respectively.

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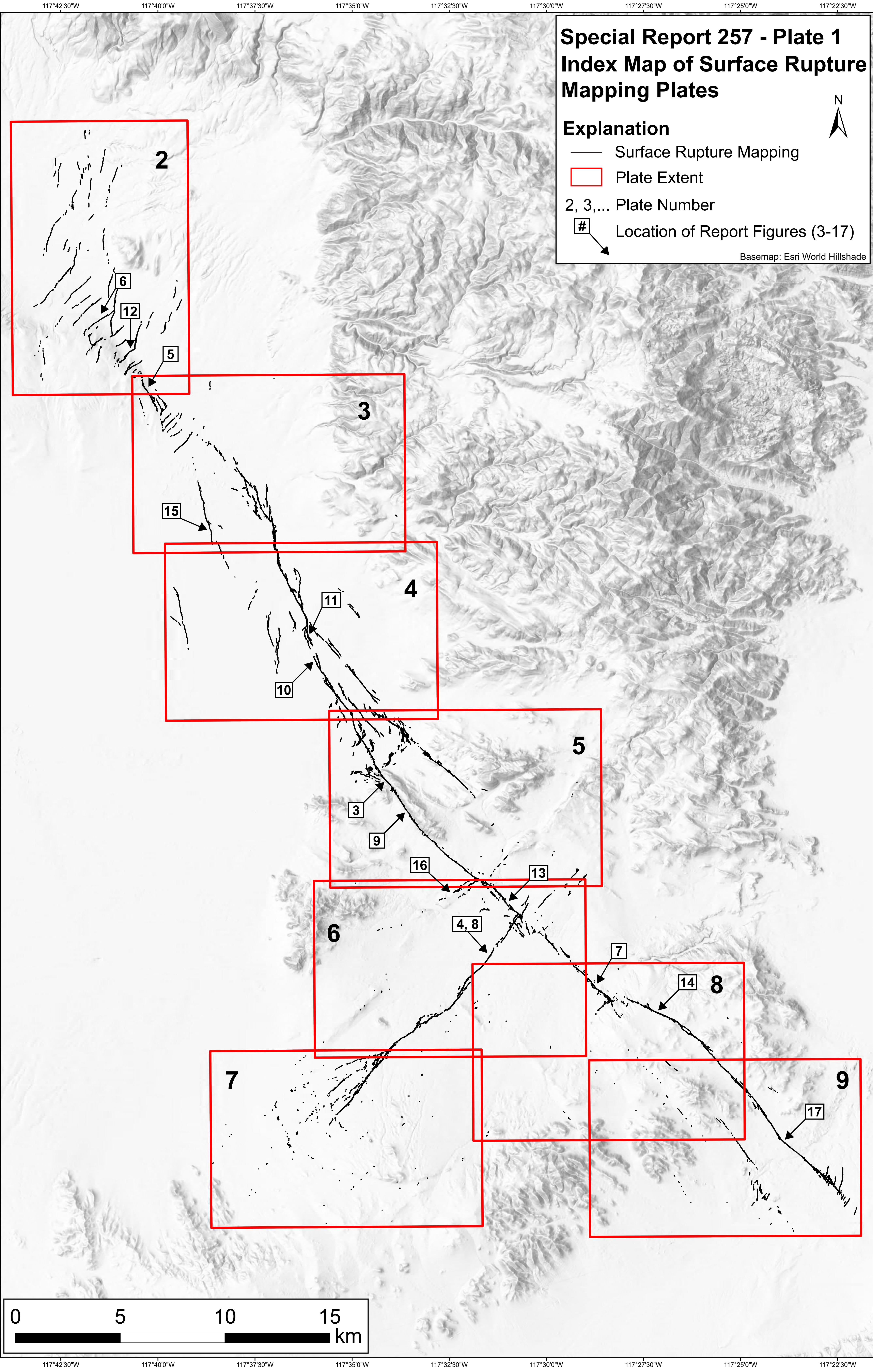
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APPENDIX (PLATES 1-9)



Special Report 257 - Plate 1

Index Map of Surface Rupture Mapping Plates

Explanation

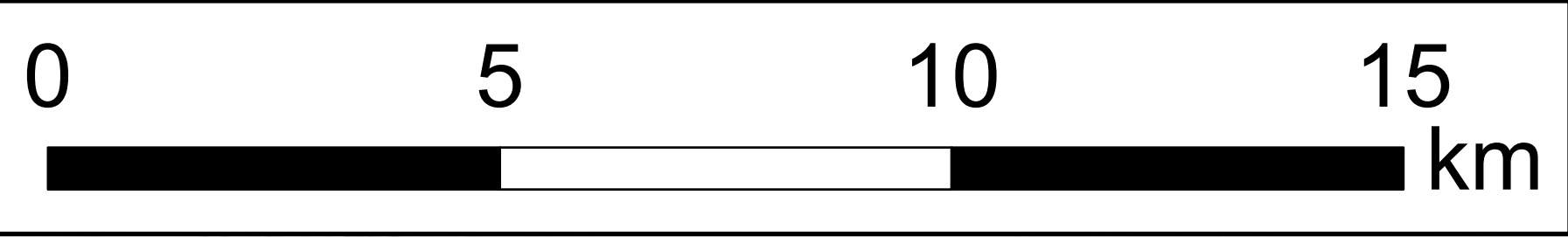
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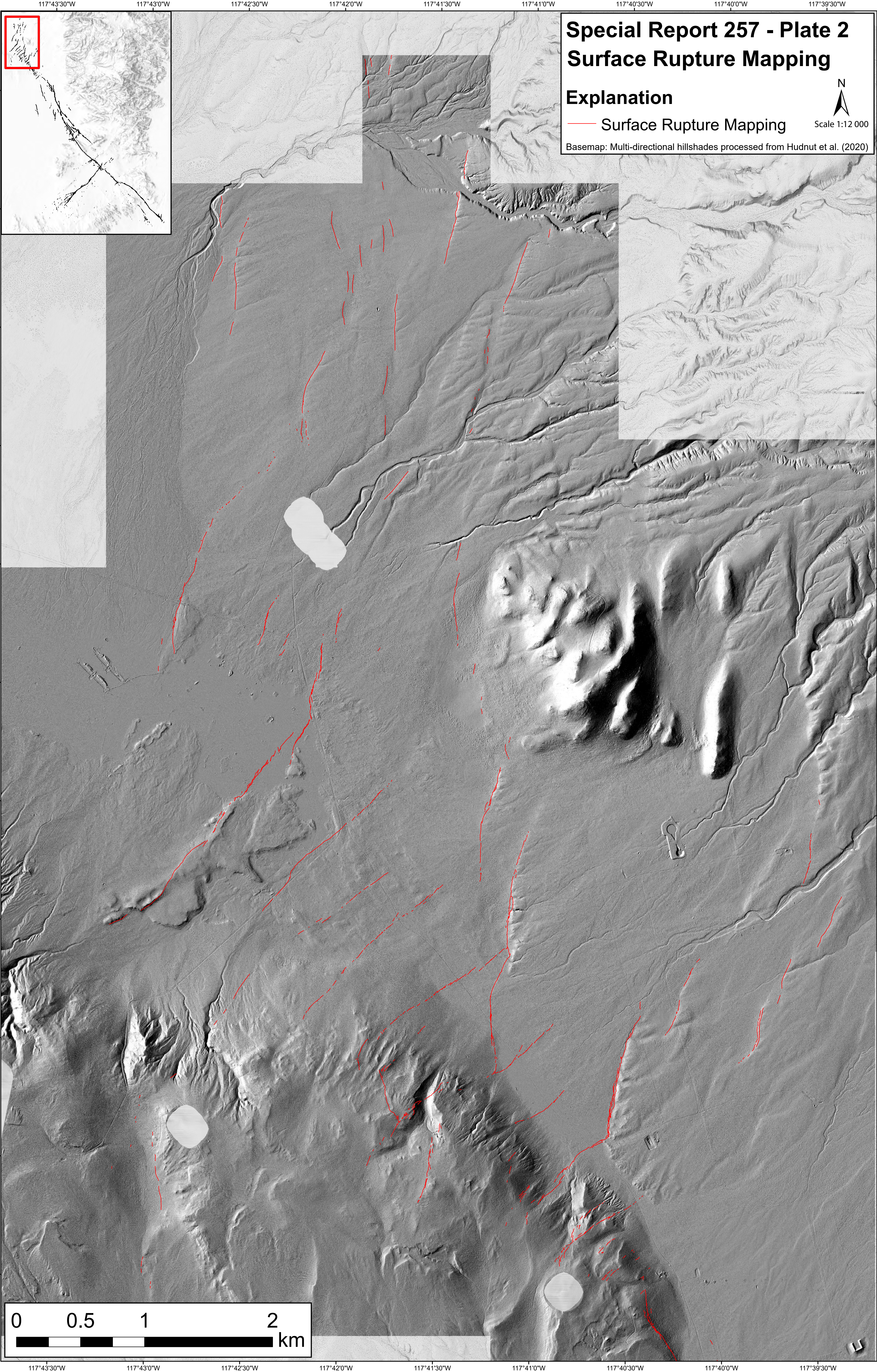
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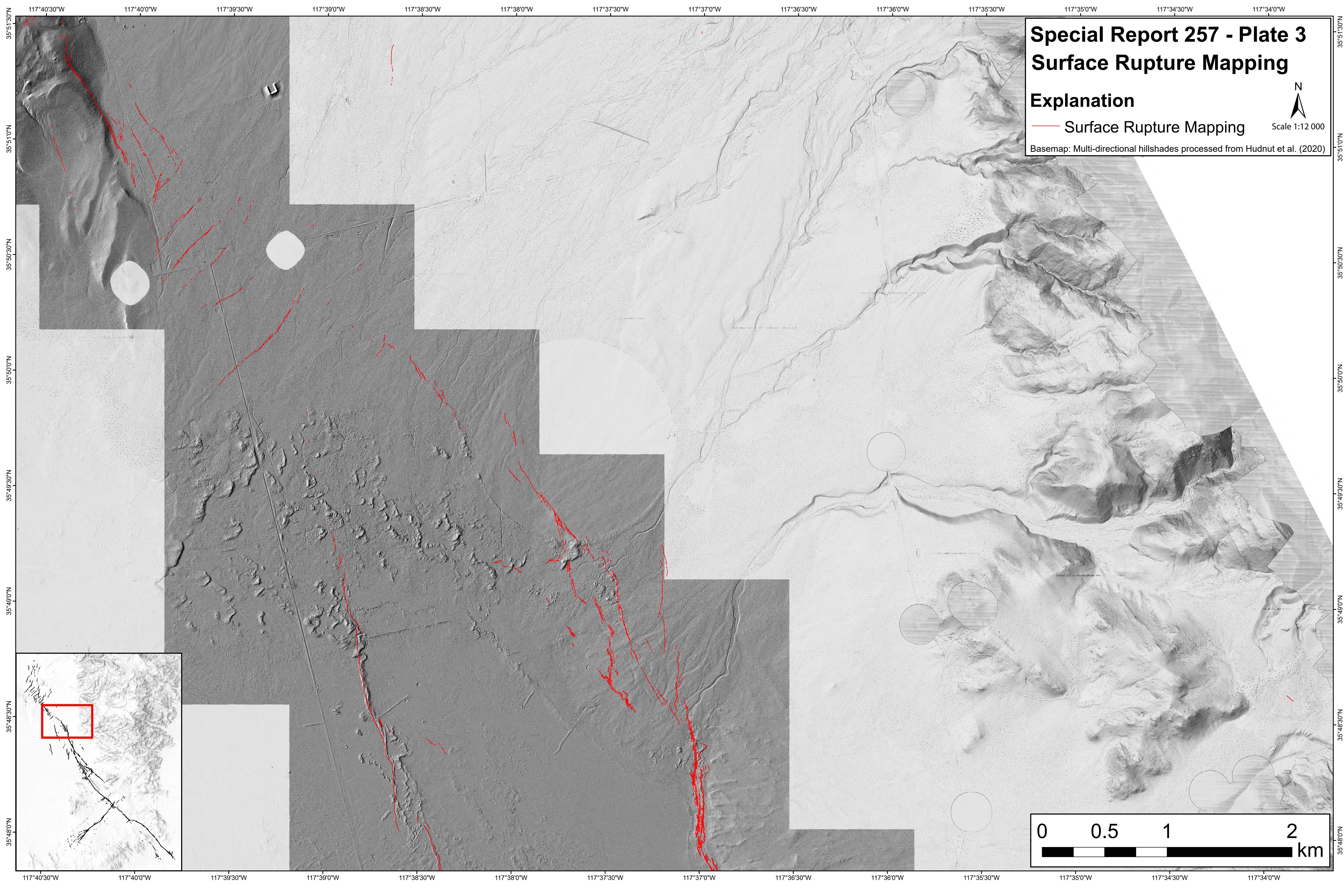
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□# Location of Report Figures (3-17)

Basemap: Esri World Hillshade







Special Report 257 - Plate 3

Surface Rupture Mapping

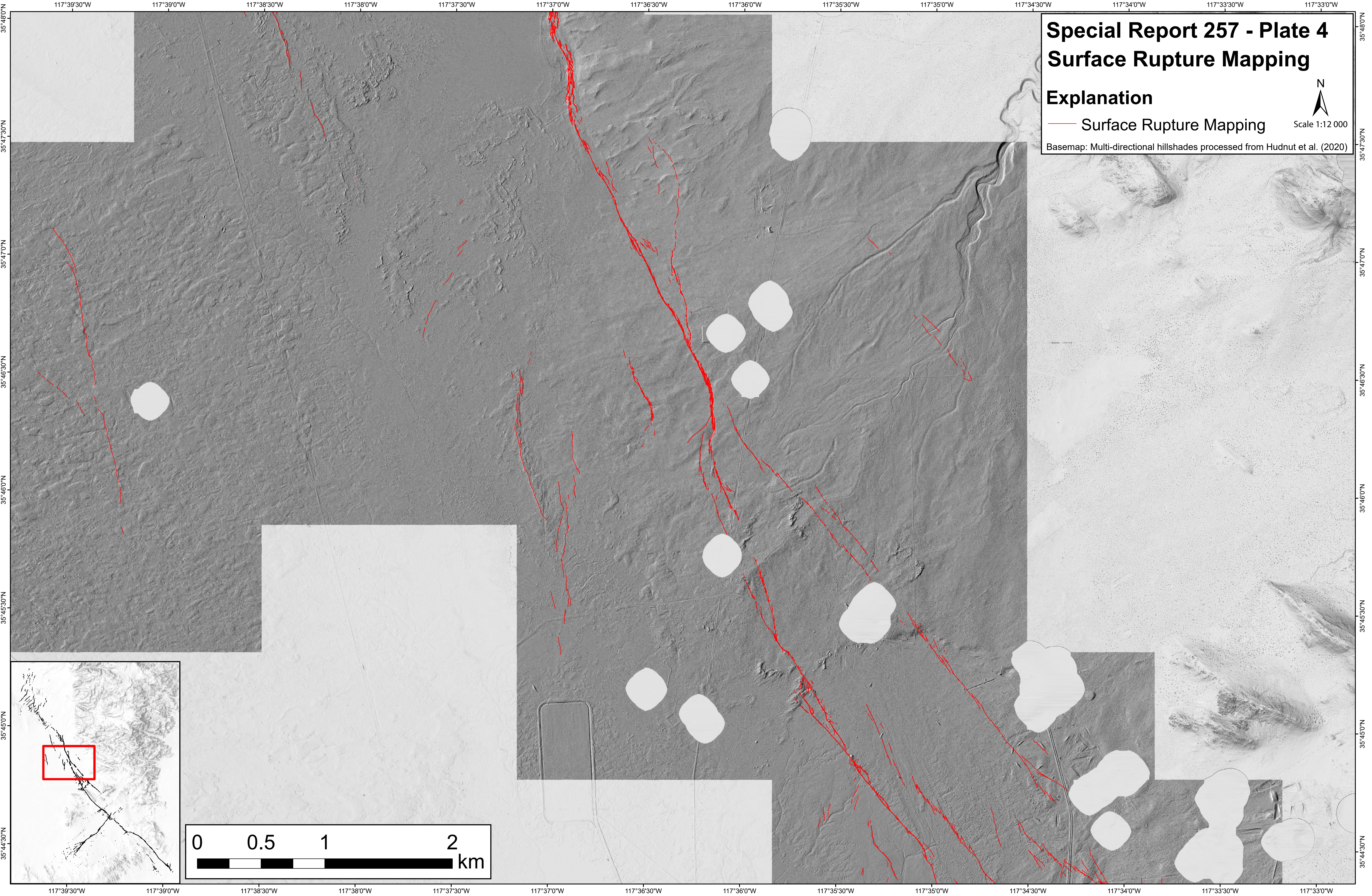
Explanation

— Surface Rupture Mapping

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Scale 1:12 000

Basemap: Multi-directional hillshades processed from Hudnut et al. (2020)

0 0.5 1 2 km

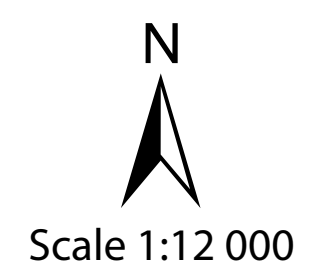


Special Report 257 - Plate 4

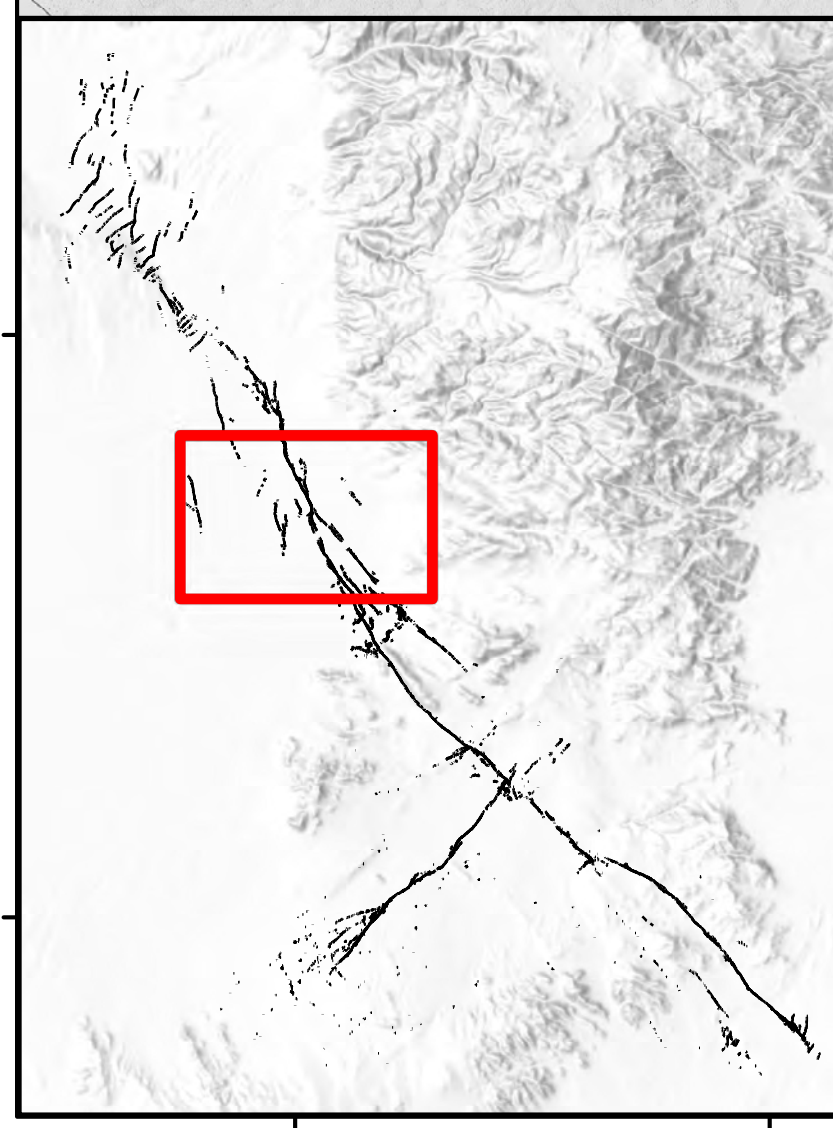
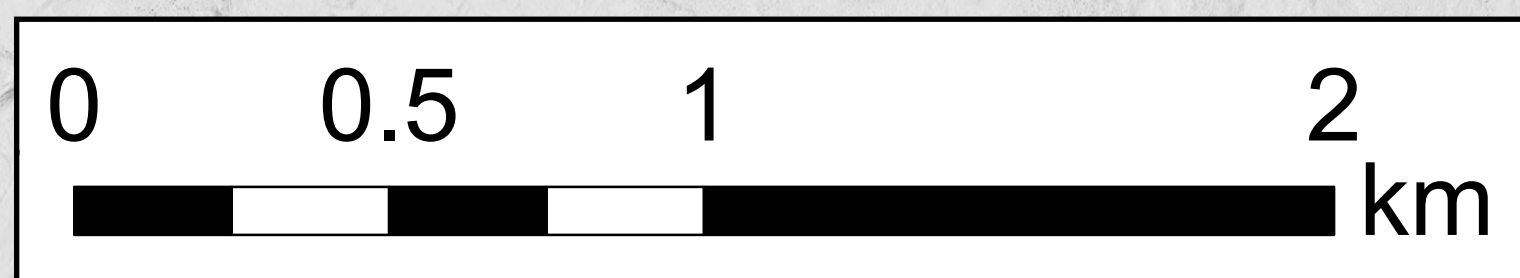
Surface Rupture Mapping

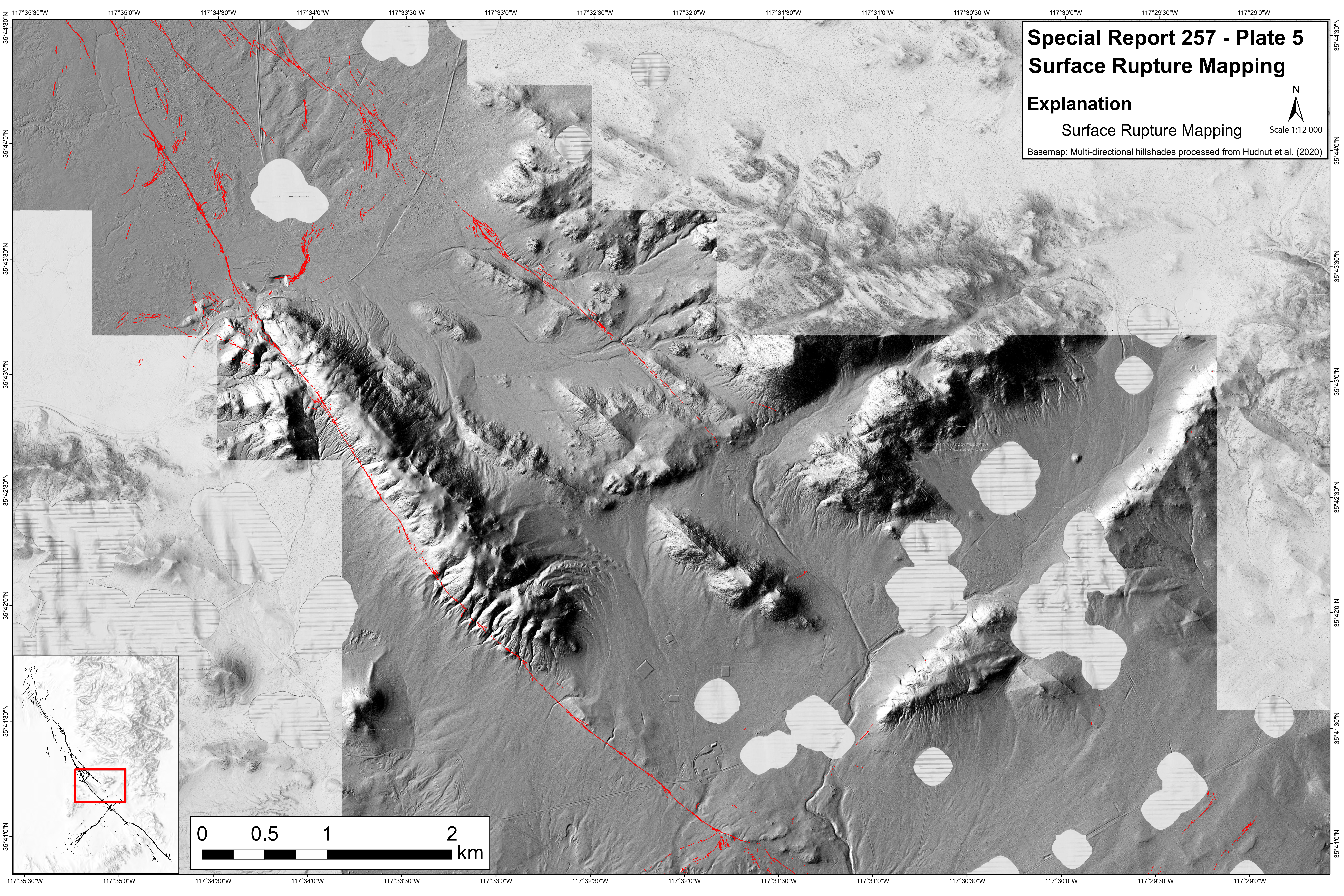
Explanation

— Surface Rupture Mapping



Basemap: Multi-directional hillshades processed from Hudnut et al. (2020)





Special Report 257 - Plate 5

Surface Rupture Mapping

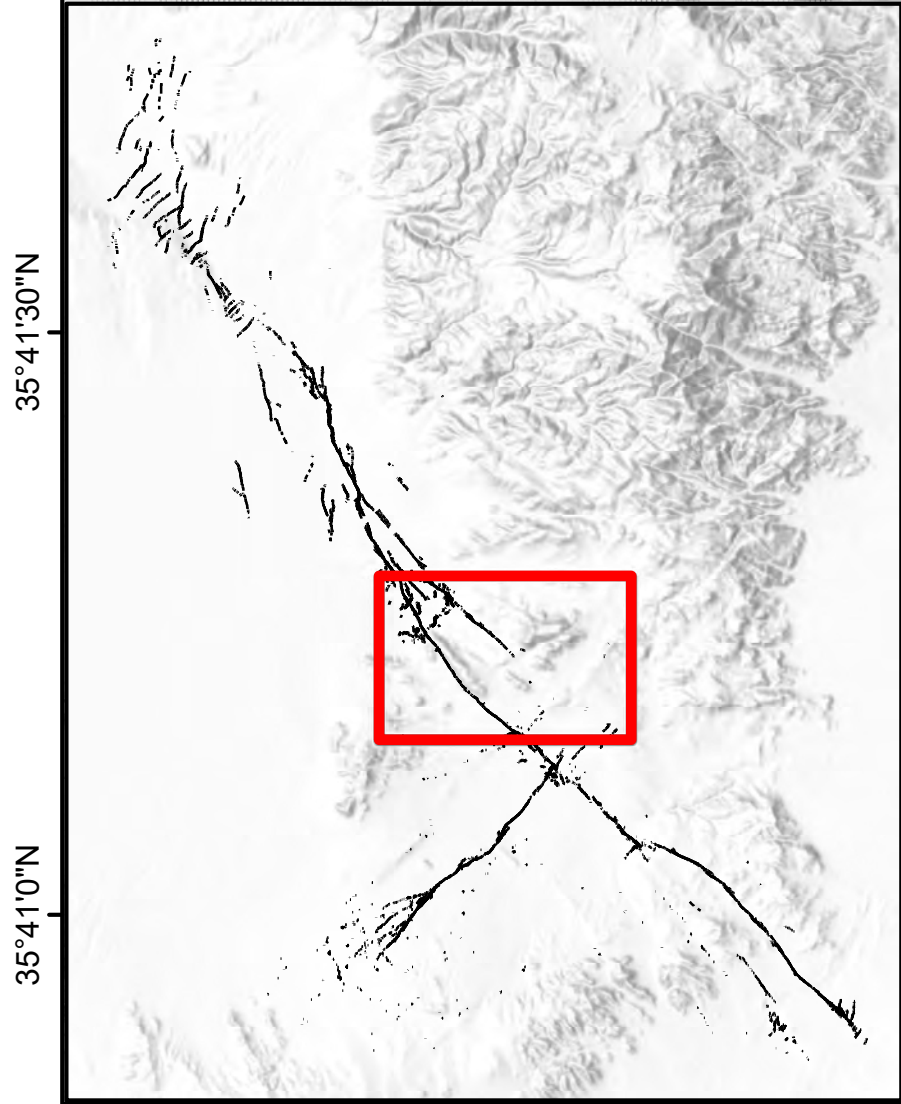
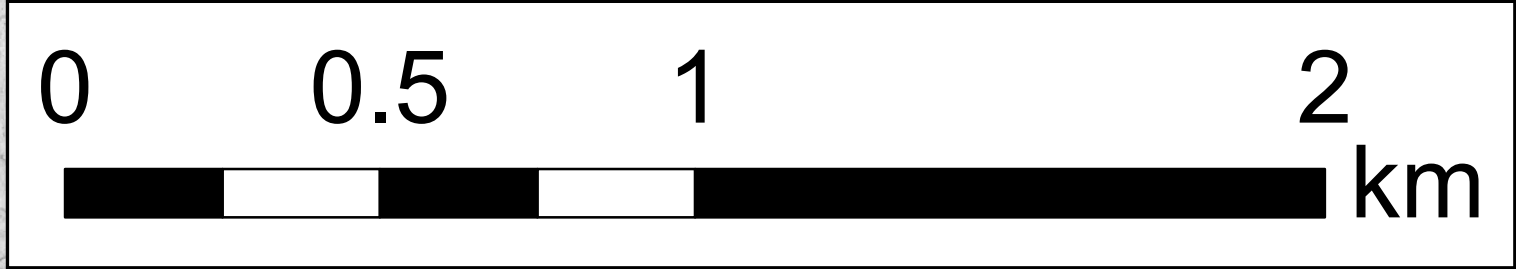
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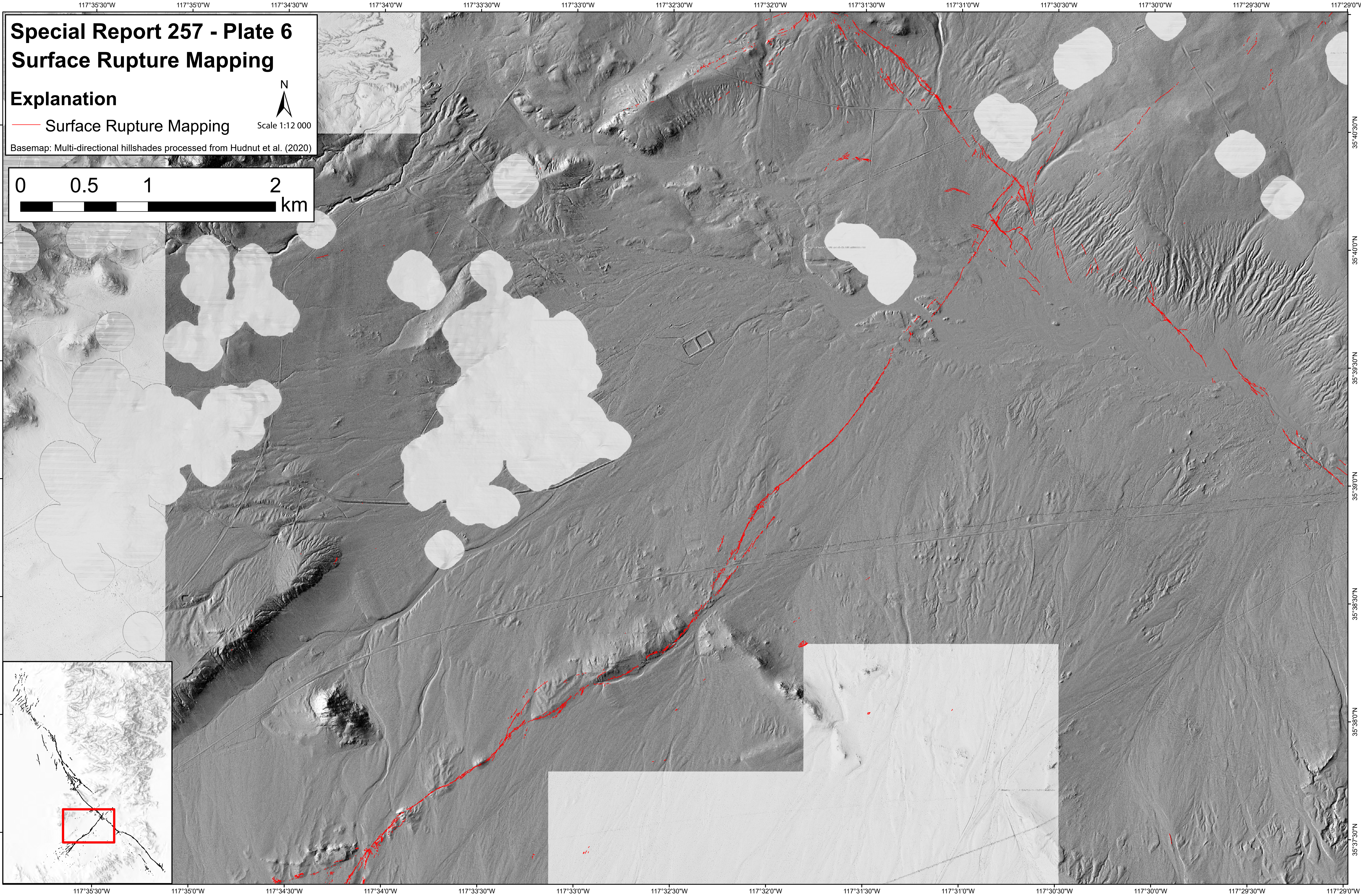
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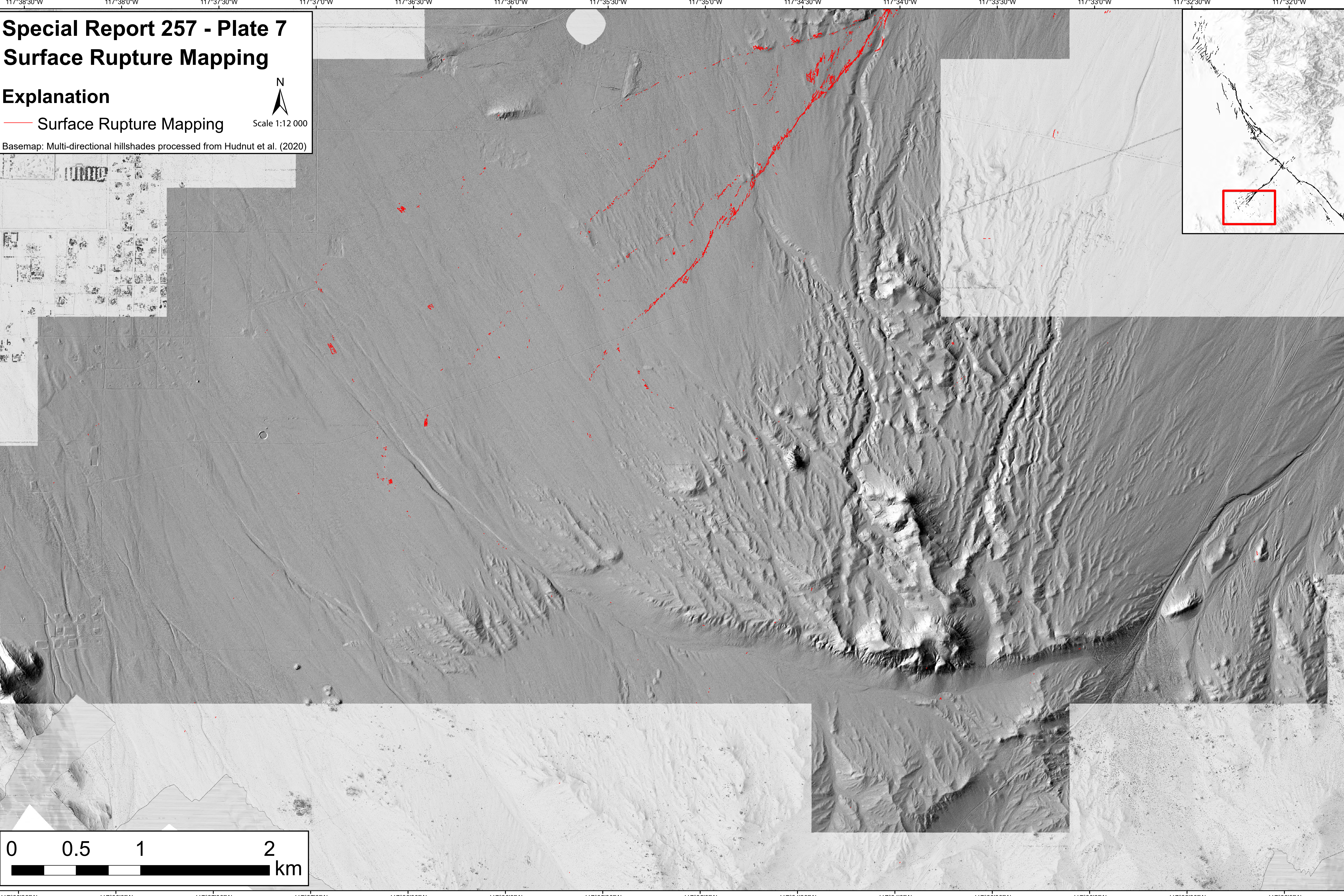
Basemap: Multi-directional hillshades processed from Hudnut et al. (2020)

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Scale 1:12 000







Special Report 257 - Plate 7

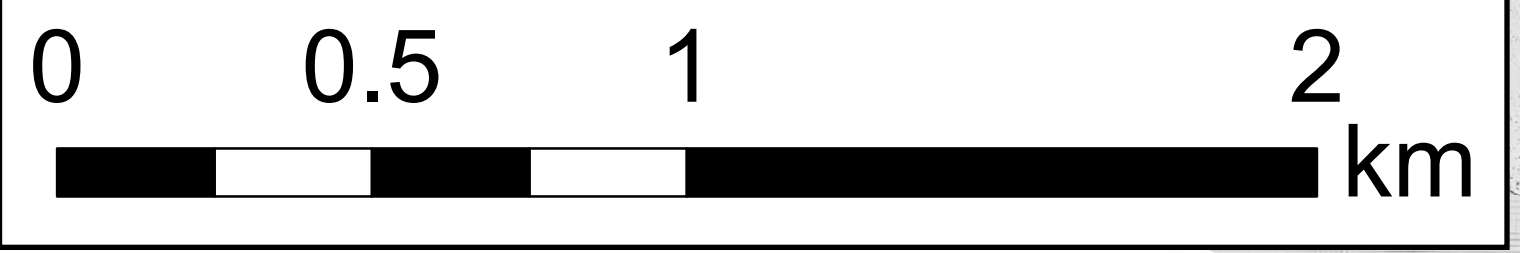
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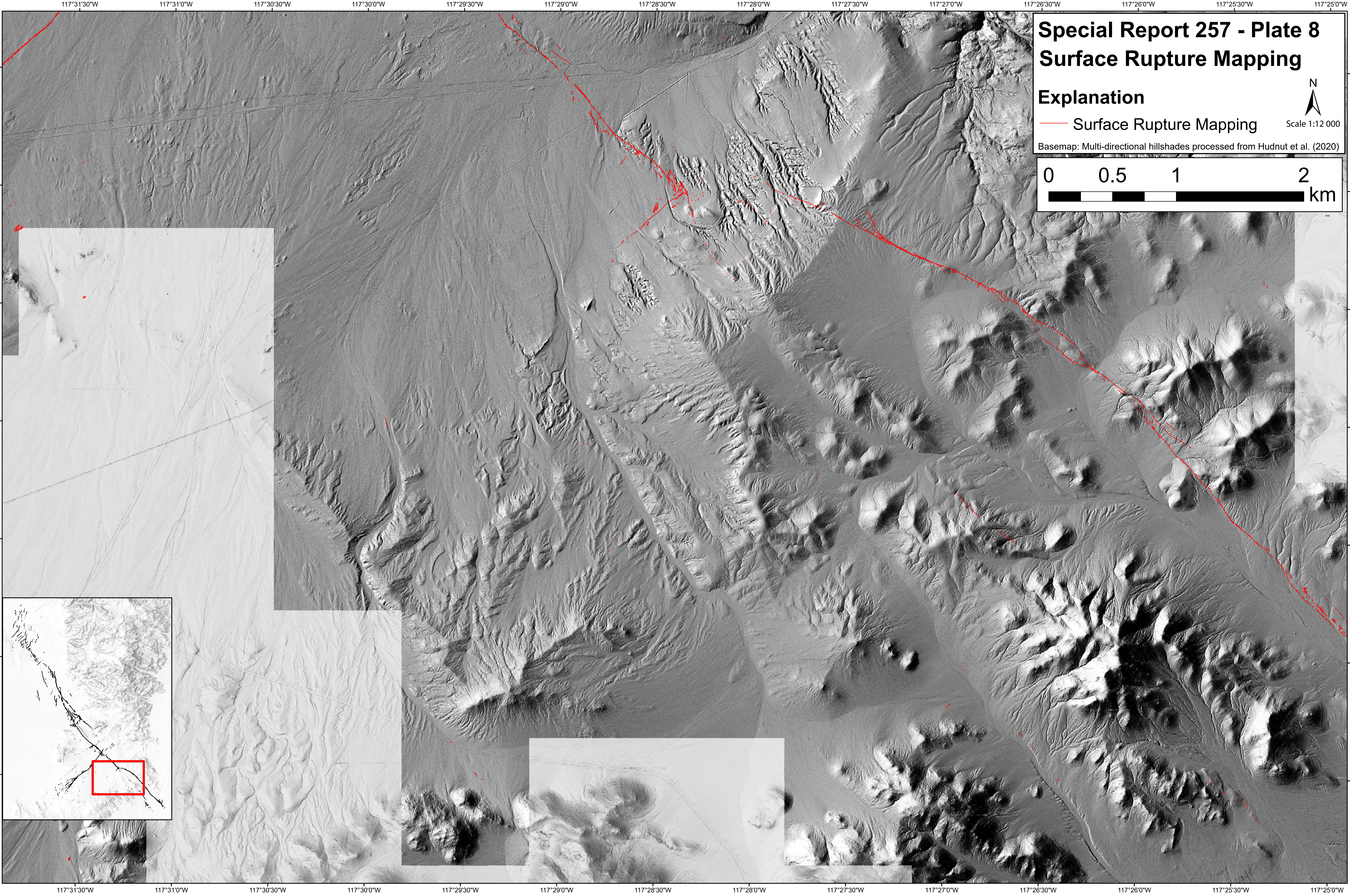
Explanation

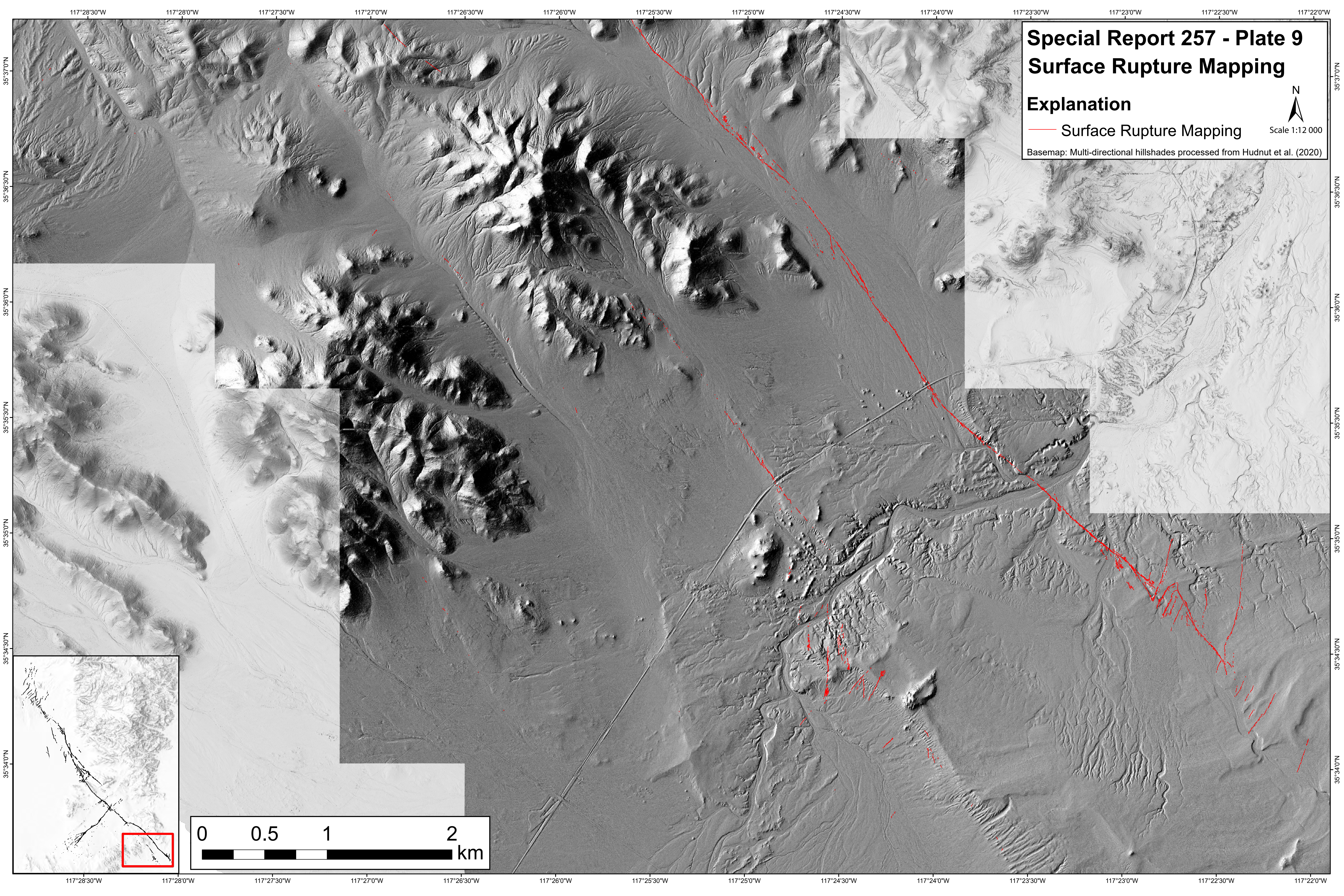
— Surface Rupture Mapping

Scale 1:12 000

Basemap: Multi-directional hillshades processed from Hudnut et al. (2020)







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Surface Rupture Mapping

Explanation

— Surface Rupture Mapping

Scale 1:12 000

Basemap: Multi-directional hillshades processed from Hudnut et al. (2020)

