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Supplementary Information for "Landslide-driven drainage divide migration"

Maxwell P. Dahlquist, A. Joshua West, and Gen Li

VERIFYING GEOLOCATION OF RIDGES

For our method of mapping divide migrations to be valid, ridges in photos must be properly georeferenced to ridges in the topography. Google Earth has some known issues with georeferencing and orthorectification in some areas that can cause mismatching between images and topography. Ridges are identifiable in satellite images where the sun angle generates appropriate shadows (Figure DR1), or where a vegetation contrast or cliff edge is apparent, and we used the correspondence of these visible ridges with the Google Earth base topography to confirm accurate referencing for the areas analyzed in this study, where possible.

Verifying the location of ridges in this manner was not possible in all images. A more widely applicable method for verifying that images are properly georeferenced is checking that streams are properly placed at the lowest points of valleys (Figure DR2). We assume that when streams are properly georeferenced, ridges are as well, such that our divide migration mapping method is reasonable to use where streams are in place. To determine whether this assumption is valid, we examine locations in our three field areas where ridges are clearly visible, and verify that both the ridge and the adjacent streams are properly georeferenced. In steep valleys, a 30-meter resolution DEM sometimes fails to capture all the fine meanders of small streams, but we find this does not necessarily indicate a poorly georeferenced image. Rather, it is a systematic displacement of the stream out of a topographic low that indicates a problematic area where ridge locations are untrustworthy. We checked more than 150 locations where ridges are clearly visible and found only 2 where streams are properly located but ridges are out of place. Figure DR2 shows an example of a properly located ridge flanked by two properly located streams. Given the good correspondence between properly referenced streams and ridges, we used in-place streams to screen areas of accurately referenced imagery for use in our analysis.

ERROR INTRODUCED BY DEM RESOLUTION

Since we calculate the amount of area captured by a landslide using the position of the ridge before the landslide occurred and define the position of that ridge based on the topography, error is introduced due to the 30-meter resolution of the DEM. The satellite photos used to identify the top of the landslide scarp have a resolution of 0.5-2 meter, so the error introduced in the area calculation by photo resolution is negligible by comparison.

We have already introduced our method for ensuring that satellite imagery is properly geolocated to the topography, and we excluded areas from our analysis where imagery was not accurately georeferenced. We thus estimate error based on properly located ridges. While ridges are not linear features, at the scale of an individual landslide we find it is a reasonable approximation to define the actual ridge as a line. To estimate the error introduced by the DEM resolution, we wish to calculate the area between the DEM-defined ridge and the actual ridge.

Approximating the location of a ridge using a 30-meter DEM results in a ridge defined by a series of points $p_0,p_1,\ldots,p_n$ spaced 30 meters apart, each of which is a distance x_n from the actual ridge (Figure S3). The area between a DEM-defined ridge of length *l* and the actual ridge it describes is defined:

$$a_e = \sum_{n=0}^{l/r} \left(\frac{x_{n-l}+x_n}{2}\right) \sqrt{r^2 - (|x_{n-l} - x_n|)^2}, \qquad (1)$$

where r is the resolution of the DEM. For a correctly located ridge, maximum distance x for any point p is:

$$x_{max} = \sqrt{\frac{r^2}{2}}. \qquad (2)$$

x_{min} is zero for a point that lies on the actual ridge. For a 30-meter DEM, we find an average x of 10.61 meters.

For each field area, we measure the total length of affected divide l and find 19,900 meters for Taiwan, 23,100 meters for Wenchuan, and 3,300 for Nepal. Applying equation 1, we obtain error estimates for our area capture calculations for each site: 1.248±0.245 km^2, 0.541±0.211 km^2, and 0.068±0.035 km^2, respectively.

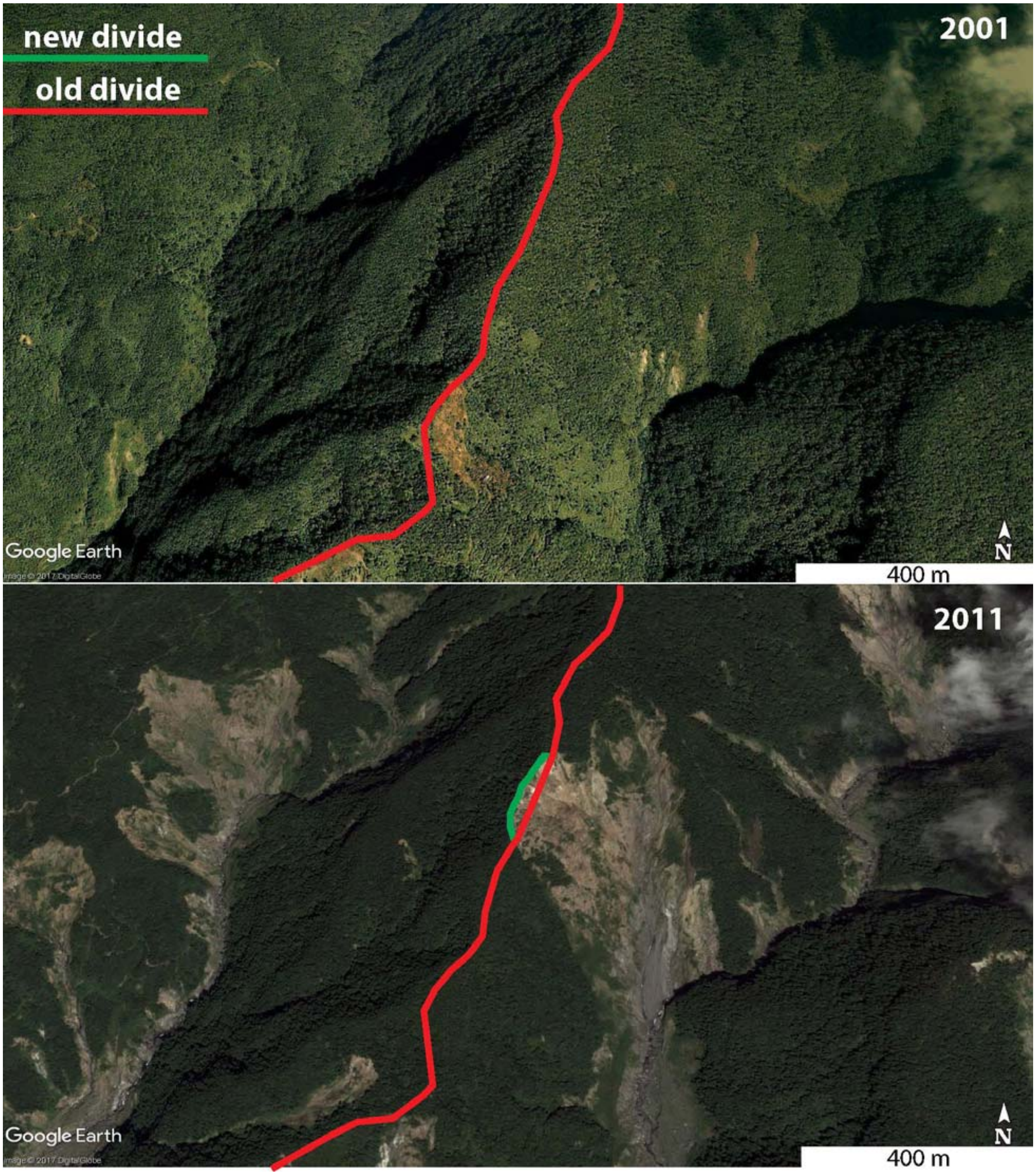

Figure DR1. Ridge identification by shadow. Images show a ridge in Taiwan before (2001) and after (2011) Typhoon Morakot, in the top and bottom panels, respectively. The ridge in the top photo is easily identified by the shadow it casts, making the divide migration caused by the landslide in the bottom image easily identifiable even without using topographic data. Throughout the study regions, we used similar instances of visibly well-defined ridges to check for accurate positioning of images with respect to topography.

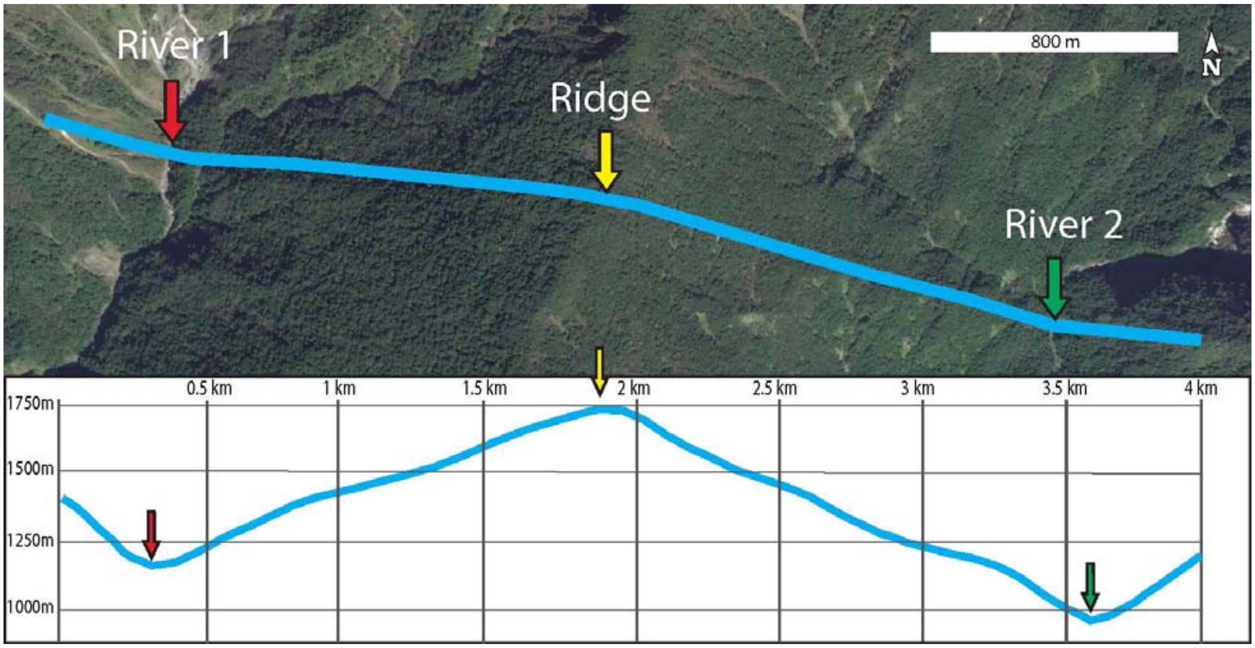

Figure DR2. Geolocation of ridges and rivers. Image shows a ridge and adjacent river valleys in Taiwan (top) and an elevation profile of the path marked in blue. Image and topography are both from Google Earth. The ridge and rivers are marked with arrows of corresponding colors in the image and elevation profile. The imagery and topography in this area are properly georeferenced. Similar evaluations were used to screen accurate georeferencing in all three study regions.

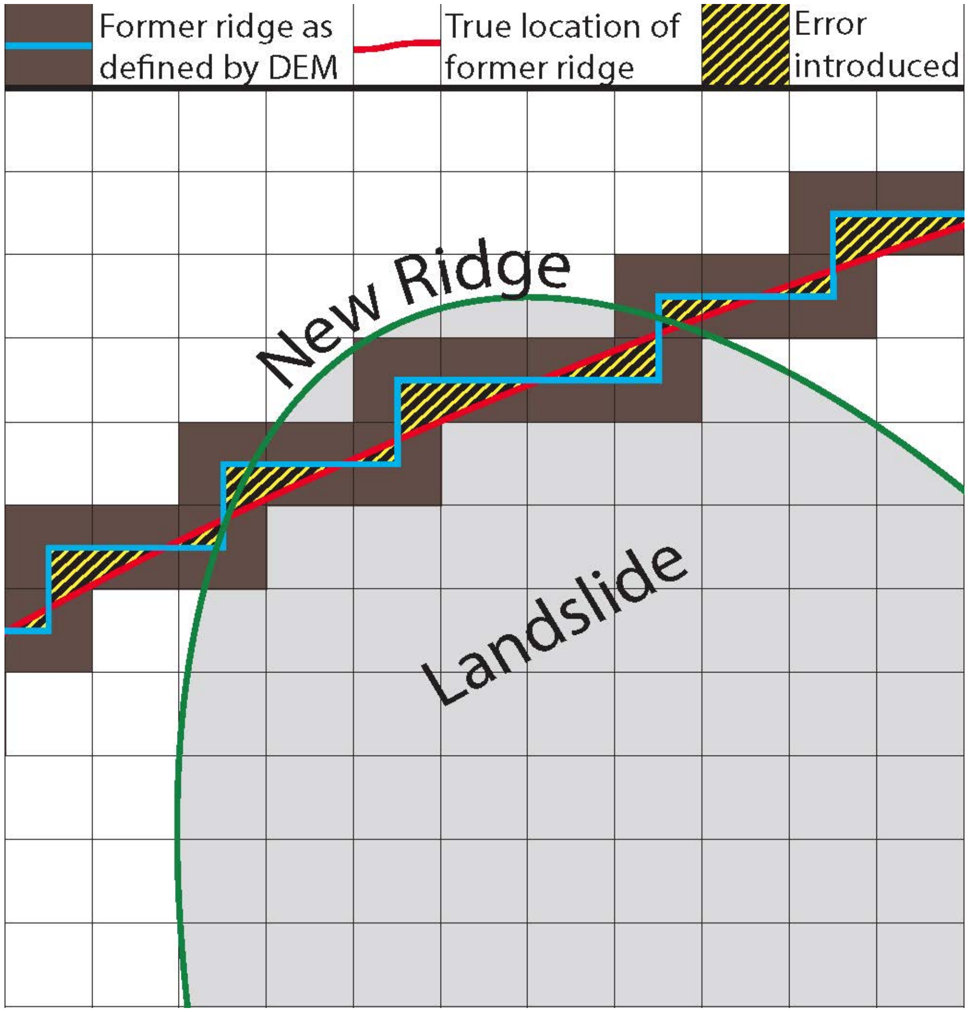

Figure DR3. Schematic of uncertainty in area calculations introduced by DEM resolution. In the error calculation, p_n is represented by the centers of the brown squares. The distance between p_n and the actual ridge shown in red is x_n.

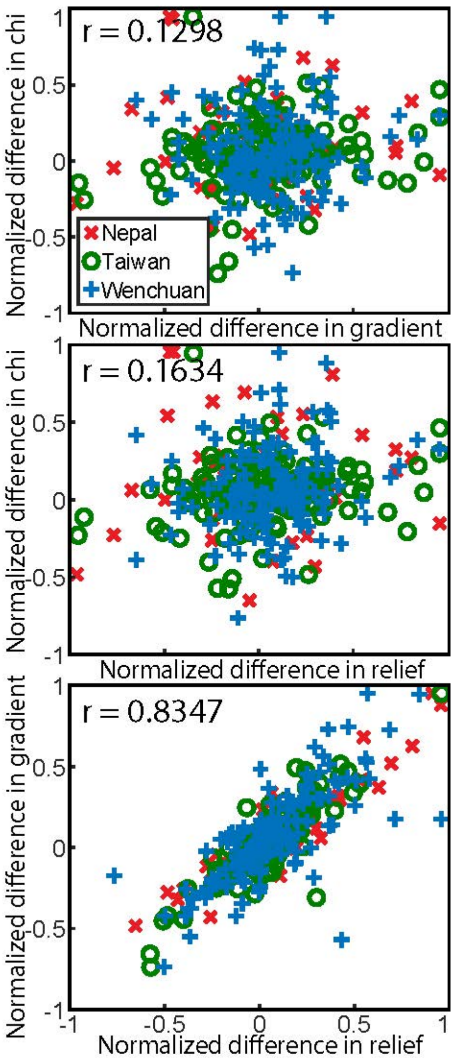

Figure DR4. Cross-divide differences in chi, relief, and gradient plotted against each other. Each point represents the difference in metrics for a single divide migration site. The strong correlation between relief and gradient is indicative that both metrics represent straightforward measures of basin geometry, i.e., a basin where rivers have a steep gradient should also have high relief as well. Calculating chi involves more assumptions and considers downstream geometry, which may lead to the lack of correlation with the other two metrics.

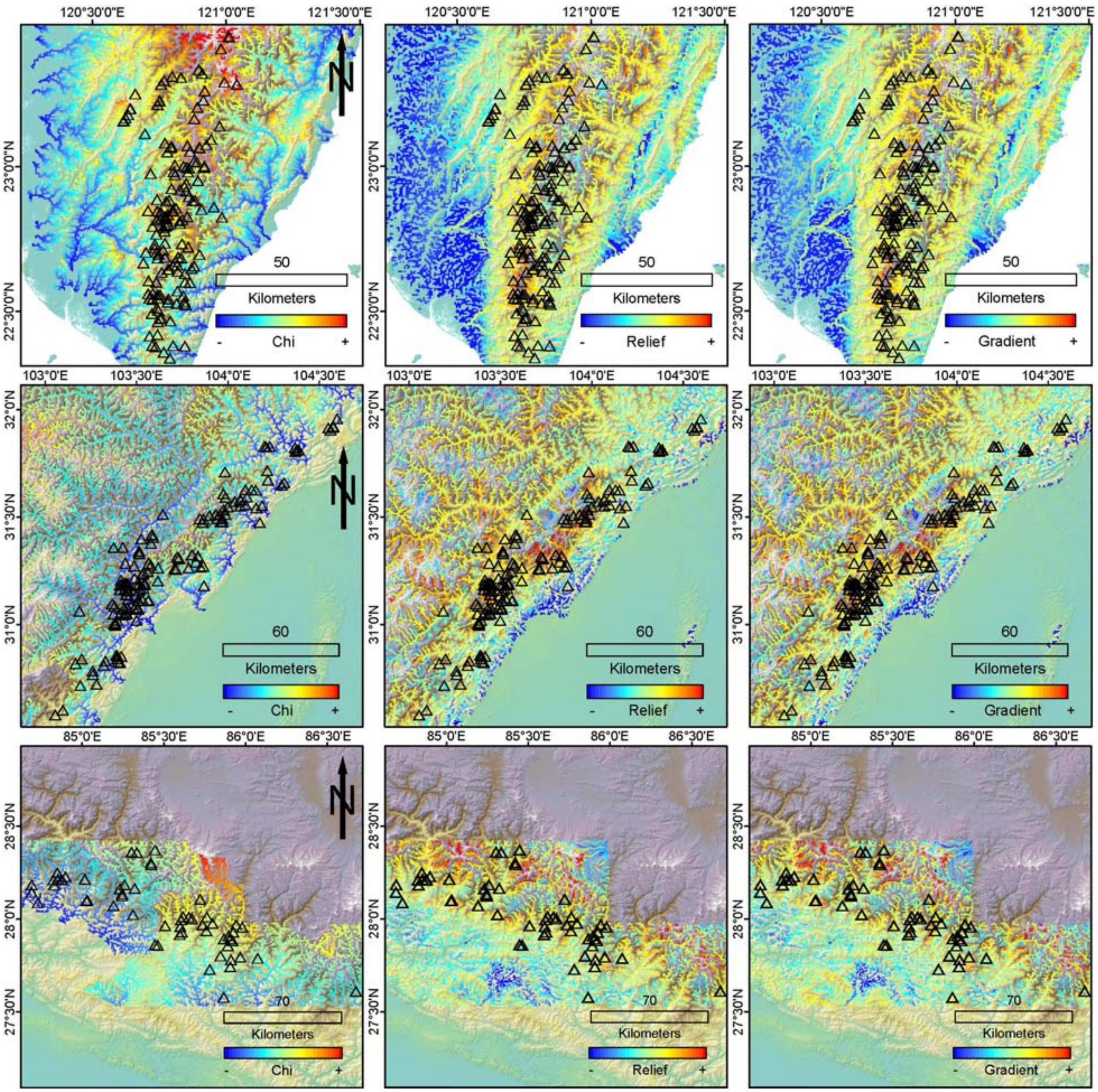

Figure DR5. Maps of relief, gradient, and chi plotted along rivers in study areas. Top row: Taiwan; Middle row: Wenchuan; Bottom row: Nepal.