Aerial reconnaissance mapping of active faults, in the Digital Age

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Abstract: *Active faults pose a hazard of surface rupture to utilities such as pipelines and electrical transmission lines. Utility corridors in North America have been assessed for active faults beginning in the early 1970s with the Trans-Alaska [Oil] Pipeline. Over the past 10 years more utility corridors have been assessed, but their length and the short time available for fault studies has led to development of this streamlined mapping procedure that uses digital imagery, computer visualization, and real-time GPS in a GIS mapping environment.*

Key words*: active faults, mapping, LiDAR*

Since 2003 the authors have performed aircraft-supported, reconnaissance active fault mapping along existing and proposed utility corridors in North America. The corridors were up to 3000 km long and crossed mainly forested terrane, for which available geological maps are at regional scales of 1:250,000 or smaller. In the beginning we used paper geologic and topographic maps, but since 2010 have switched to digital mapping.

THE OBJECTIVE

In order to locate active faults in and near the utility corridor, we flew over every fault shown on published maps to look for evidence of Quaternary displacement. We chose this time-consuming approach because we could not, *a priori*, disprove that even an old fault might have experienced a reactivation event in the Holocene or late Pleistocene.

THE TERRANE

Utility corridors follow the gentlest terrane (topographic lows such as valleys) if such features lead toward its destination. But inevitably, there will be rugged terrane elements that trend perpendicular to the corridor and must be crossed, such as the mountain range shown in Fig. 1. A drawback of mountains at high latitudes is that they were recently deglaciated (15-18 ka), so evidence for postglacial faulting on low slip-rate faults may exist only as single displacement event of a meter or two.

Fig. 1. Typical terrane traversed by North American utility corridors.

THE PERSONNEL

Our Mapping Team usually consists of four persons: a Lead Geologist, a 2nd Geologist, a Computer Operator, and a Bear Guard (necessary for field traverses). The Lead Geologist determines the strategy of the mapping, directs the pilot in the air, and views features ahead and on the left (port) side of the aircraft. The 2nd Geologist views features on the right (starboard) side of the aircraft. The Computer Operator manipulates the main computer while in the air, at the direction of the Lead Geologist.

THE AIRCRAFT

Helicopters are preferred over fixed-wing aircraft because: (1) they can fly lower and slower than fixed-wing aircraft, (2) they can hover briefly if necessary for examining exposures where it is impossible to land, and (3) they can land in small clearings.

Fig. 2. Mid-size helicopters can land in many places for field-checking.

Many helicopter models will seat five passengers, but we normally prefer a larger helicopter (such as the Bell 212, or "Huey") due to their better visibility out the windows, and their larger interior space needed for the computer equipment. All passengers and the pilot must be able to communicate with each other via headsets. Comfort is a secondary issue, even considering flying 8 hours per day over many days. The pilot and mechanic can be very helpful if they clearly understand the goals of our mapping, for example, in setting up a working communication system, in providing electrical power for the computer system, and arranging seating comfort.

THE DIGITAL DATA SETS

The computers should be loaded with all available data sets, correctly georegistered, so layers can be quickly displayed in the GIS software (we used Global Mapper v11 and v14). Data layers include:

1- The corridor centreline with numbered kilometre points along it.

2- All geologic maps showing faults; scanned versions saved as TIFFs or JPEGs. OPTION: hand-digitize the faults as a vector layer, so they can be overlaid on a raster map such as a DEM.

3- Topographic base maps (raster)

4- Published DEMS (10 m, 30 m)

5- Bare-earth LiDAR DEMs (1-2 m); normally available only in the 1 km-wide strip along the utility centerline

6- Orthophotographs (1-2 m)

THE COMPUTER SYSTEM

We used two computers in the air, a main one (Panasonic Toughbook 31) and a 2nd one (Lenovo X100e notebook). Both were GPS-enabled, via an internal GPS (main), and an external handheld GPS connected to the 2nd computer by a USB cable. Both computers were taken on some field traverses, but the ruggedized Toughbook performed better.

Fig. 3. The Computer Operator (left) controls the visible layers and geographic area of the display, according to directions of the Lead Geologist (right), who sees the same display on a large monitor at his feet

Probably the most important aspect of the airborne computer system is how fast you can display new layers on the monitors. At a speed of 200 km/hr, the helicopter travels 55 m every second. If it takes 10 seconds to change displays for the Lead Geologist, the helicopter will have travelled 550 m. If the feature of interest is now behind you, the helicopter must turn around. Each turn-around costs time and fuel, and reduces the total kilometres of faults that can be surveyed each day. We found that large raster files of geologic and topographic maps (such as uncompressed TIFF files) take too long to display at the speed of the helicopter. Although GIS professionals prefer this file format for office work, we had to shrink the files by decreasing the resolution and/or compressing them to JPEGs.

MAPPING IN-FLIGHT

The key feature of our system is the large (17") computer monitor at the feet of the Lead Geologist (Figs. 3, 4). This display is fed from the main computer operated by the Computer Operator behind him. The Lead Geologist views the geologic map displaying the faults, so he can direct the pilot to fly down the length of each mapped fault. The pilot can also see the monitor, which permits him to see if he is flying right above the fault trace.

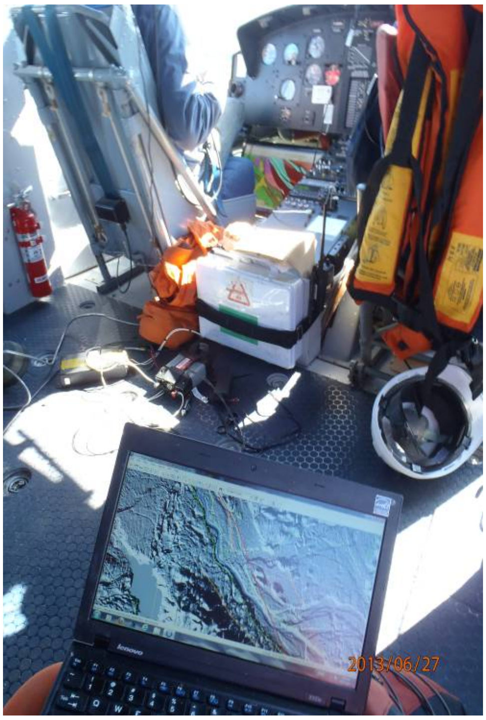

Fig. 4: The Second Geologist maps geomorphic scarps and lineaments on-the-fly on a DEM (foreground) using a GPS-enabled computer. The monitor at the Lead Geologist's feet (top, center) shows the geologic-tectonic map of the same area.

The Lead Geologist sits in the co-pilot seat and thus can view the fault trace ahead and to the left side (Fig. 5). The 2nd Geologist views terrane to the right and maps lineaments and all types of scarps (Fig. 6). The Computer Operator is usually too busy to look out the windows, but may have to observe left-side terrane if the Lead is busy writing notes.

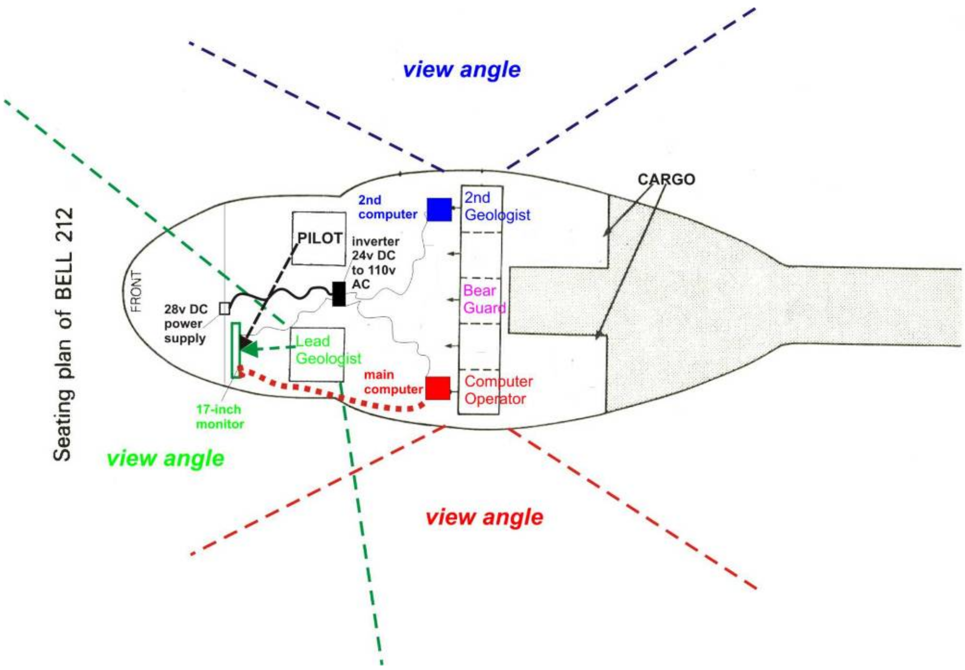

Fig. 5. Interior arrangement of the aerial mapping team in a Bell 212 helicopter. Green, blue, and red indicate the stations and view angles of the Lead Geologist, 2nd Geologist, and Computer Operator.

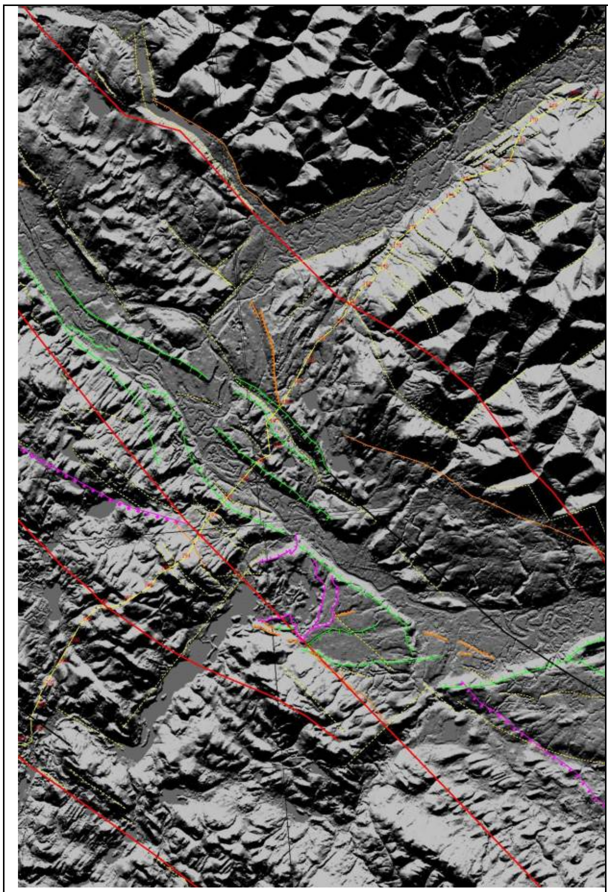

Fig. 6. Example of aerial mapping on a 30 m DEM; width of map is 30 km. Red lines, regional strike-slip faults; purple lines with diamonds, regional thrust faults; all from published maps. Yellow line with red numbers crossing from upper right to lower left, centreline of utility corridor. Colored lines show scarps with hachures on down side; green, fluvial scarps (erosional); purple, landslide headscarps; orange, scarps of unknown origin (targets for detailed examination). Yellow dotted lines, lineaments.

THE PROBLEM WITH FAULTS

Determining whether an active fault crosses a utility corridor is complicated by some basic issues described herein.

1- Faults often cannot be traced into utility corridors that occupy valleys, because valley floors are covered by young deposits (alluvium, glacial deposits). This may be true even for regional faults extending for long distances on either side of the corridor. In such cases it is reasonable to assume that the bedrock fault continues across the corridor in the subsurface, and thus future surface rupture (if it occurs) will cross the corridor.

2- The definitive evidence that a fault has (or has not) Moved in the Holocene may be preserved at only one or two small locations along the fault. The probability of those locations being within the utility corridor is thus very small, especially on long faults. Conversely, in order to look for definitive evidence, one must extend the surveys along the fault trace for many km to tens of km away from the utility corridor. A rule of thumb would be to survey long regional faults at least 100 km away from the corridor in both directions.

3- Faults that trend perpendicular to the corridor are the easiest to assess from a geometric standpoint, because the area of their intersection with the corridor is minimized. Conversely, faults that intersect the corridor at a very low angle are the most problematic, because they can cross the corridor for long distances. Slight changes in the strike of the fault or in the orientation of the utility centreline can greatly change the number of fault crossings.

4- In forested areas small-scale landforms (scarps, ridges, gullies) less than about 5 m high cannot be detected from the air, unless they are accompanied by a strong difference in vegetation. Even when they are detected from a vegetation contrast, their exact size and shape cannot be observed, so their origin cannot usually be deduced (erosional vs. depositional vs. tectonic).

5- Landforms less than 5 m high can be observed in clear-cut areas, but only if the clearcuts are less than about five years old. After that, regrowth of trees again obscures the landforms. *The only way to detect small scarps and lateral offsets in forested areas is with bare-earth LiDAR DEMs of 1 m to 2 m resolution.*

6- The inability to visually detect fault scarps less than 5 m high in uncut forests poses a general constraint on the detectability of young faulting by aerial reconnaissance. What types of faults might be undetectable? One example would be a "slow" fault with a long-term slip rate of <0.33 mm/yr. Such a fault would not be expected to generate more than 5 m displacement in 15 ka, so would essentially be "invisible" to the aerial reconnaissance. Another example would be a "slow" fault with a long-term recurrence interval greater than 15 ka. A third example would be a strike-slip fault with little to no vertical displacement. The detection threshold for lateral fault offsets in a forest may be 2-3 times larger than the 5 m vertical threshold.

7- In order to design a utility crossing of an active fault, paleoseismologists must determine the displacement parameters of recent surface ruptures: strike and dip of the fault, sense of slip, and orientation and magnitude of the net slip vector (plus and minus any uncertainties). As with the age information, this type of structural information is likely to be preserved at very few places along the fault, and not likely within the corridor itself.

RECOMMENDATIONS

Managers of seismic hazard assessments in utility corridors need to understand the limitations of aerial reconnaissance for detecting Holocene faulting, particularly in forested regions. At present, bare-earth LiDAR DEMs offer the only way to recognize scarps smaller than 5 m high and lateral offsets several times larger. Unfortunately, most utility corridors are covered by a narrow strip of proprietary LiDAR DEMs only along the corridor centreline (typically 1000 m wide). As explained previously, the key evidence for Holocene movement and for critical fault displacement parameters are not likely to fall within such a narrow strip.

The success probability of the surface rupture assessment will be greatly increased if the LiDAR coverage is extended along the faults to some distance beyond the corridor. The exact distance depends on the length of the fault and its distance from the corridor. For short faults (<10-20 km long) in or near the corridor, the entire fault length should be covered. For longer faults (20-100 km long), the first 20-30 km outside the corridor should be covered. For regional faults, it may be necessary to extend the LiDAR out 50-60 km away from the corridor in both directions. The strip of LiDAR along the faults does not need to be very wide; 2 km should be sufficient unless the fault zone is wide and complex.

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