Seismic CAT-Scan of an Ancient Earthquake

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November 18, 1997
ABSTRACT

Two-dimensional and three-dimensional seismic surveys were conducted across the Oquirrh fault, Utah with the purpose of imaging the fault structure to a depth of about 15 m. Results show that the 3-D tomogram clearly delineates the fault zone and a colluvial wedge, both of which correlate extremely well with the geologic cross-section interpreted from an adjacent trench. The thickness of the colluvial wedge image is used to give a moment magnitude estimate of 6.8 for the most recent earthquake on this fault, which is in close agreement with the 7.0 estimate based on a nearby trenching study. This study demonstrates, for the first time, that seismic imaging methods can be used to accurately estimate the size of prehistoric earthquakes. Thus, seismic tomography has the possibility of providing cheaper, deeper and wider, but less resolved, images of fault systems than the intrusive excavation of trenches across faults.

INTRODUCTION

The primary goal in paleoseismology is to estimate the sizes and recurrence intervals of ancient earthquakes (1). Until now, such information has typically been obtained by trenching across a fault and examining the geologic cross-section for signs of past faulting activity. Correlating this activity with, typically, radiocarbon dates of soil in the trench can give an estimate of the recurrence interval of an ancient large earthquake. Such information is invaluable in estimating the earthquake hazard of a region and the time frame for a future large earthquake.

For normal faults, such as those that occur in the Intermountain Seismic Belt (2), trench
excavations are used to identify the presence and shape of colluvial wedges. A colluvial wedge is a wedge-like zone that is filled with rubble immediately following a surface rupturing event, and is the characteristic geologic signature of an ancient earthquake that ruptured the ground surface (1).

Figure 1 depicts the sequence of geologic cross-sections prior to and following a normal-fault earthquake. Here, larger earthquakes produce greater displacement along the fault, so that wedge thickness is proportional to earthquake magnitude. In addition, the depth interval between neighboring wedges is proportional to the recurrence interval between large events, assuming a constant sedimentation rate. This assumes a constant sedimentation rate. Thus a typical trench study across the, e.g. Wasatch Fault, will attempt to delineate the locations and thicknesses of colluvial wedges and use this information to determine earthquake recurrence intervals and magnitudes.

The problems with trench excavations are that they are expensive, environmentally intrusive so that they are limited to sparsely populated zones, and are typically limited to depths of about 9 m. This limited depth range restricts the study of ancient earthquakes to a limited span of geologic time. Moreover, a trench only reveals a 2-D cross-section of the geologic record and so it cannot fully assess the geologic effect of the oblique-slip movement.

To overcome the limitations of the trenching methods, geophysicists (1, 3, 4, 5) have attempted to use seismic methods to image the shallow structure of faults. Their use of the seismic reflection method could pinpoint the location of the fault, but could not unambiguously identify the shapes, locations or thicknesses of colluvial wedges. In referring to the work of Stephenson et al. (1993), McCalpin (1) states "However, seismic methods could not
differentiate individual colluvial wedges 1 to 2 m thick against the main fault plane, and thus
could not independently determine the number of or size of prehistoric displacements.”. It is
not easy to clearly image colluvial wedges with reflections because the noisy near-surface en-
vironment promotes severe scattering, strong surface waves, and static problems in the data.
Nevertheless, there are hints of 3-4 m thick colluvial wedges in the bottom part of Figure 13
in (5), which suggests further research in using reflection imaging as a tool for colluvial wedge
identification.

To overcome the problems associated with reflection imaging, we proposed in 1996 to
conduct seismic CAT (computer axial tomography) scan experiments (6) over the Oquirrh
fault, Utah with the intent of inverting first-arrival traveltimes for velocity tomograms. The
key idea is that the first arrival traveltimes are not affected by near-surface scattering or
surface wave problems, and so could be used to image the colluvial wedge. The implicit
assumption was that the seismic velocity of the colluvial wedge was significantly slower than
the surrounding alluvium, as shown in Figure 2. If this assumption was invalid, then the
tomography experiment would have failed to reveal the presence of the wedge.

SEISMIC EXPERIMENT

In the spring of 1996 and 1997, researchers at the University of Utah conducted 2-D and
3-D seismic experiments across the Oquirrh fault, Utah (see Figure 3). The scientific objective
was to use the resulting reflectivity and tomographic images to deduce the paleoseismic history
of this fault zone. The 3-D seismic data (112,896 traces) were collected over a 44.2x9.1 m²
patch of ground along the Oquirrh fault, the first arrival traveltimes were then picked, and
these traveltimes were inverted by a 3-D tomographic technique (7). Figure 4 shows the shot-
receiver geometry. To complement information from the 3-D tomogram, a 2-D reflectivity
image was obtained from a 173.8 m long reflection survey that cut perpendicularly across the
fault.

SEISMIC CAT SCAN RESULTS

Figure 5 shows the 3-D seismic CAT scan, i.e., velocity tomogram, obtained by inverting
83,570 first-arrival traveltimes picked from the 3-D data. A Multigrid SIRT-like (simultaneous
iterative relaxation tomography) method (7) was used to invert these data, and 20 iterations
were used to reduce the RMS (root-mean-square) traveltime residual to about 0.006 sec.
Slicing the 3-D tomogram at an offset of $y = 3.1$ m reveals the wedge-like image shown at the
bottom of Figure 6. For comparison, the top figure is the geologic cross-section (8) sketched
from the trench excavated about 12.2 m to the north. The dark line denotes the geologist’s
interpretation of the wedge, and bears a remarkable resemblance to the wedge-like image in
the tomogram. We believe that this image represents the first example in which the 3-D shape
and location of a colluvial wedge has been unambiguously imaged by a seismic technique.

Figure 7 shows the 2-D seismic reflectivity image obtained by Common Depth Point (CDP)
processing and poststack migration (9) of the seismic reflection line. Although the colluvial
wedge is not clearly delineated in this profile, it does reveal the geometry of the shallow strata and an antithetic fault west of the main fault scarp. The next section shows how the dip angle of this strata can be used to estimate the magnitude of the earthquake associated with the colluvial wedge.

**MEASURING DISPLACEMENT FROM THE COLLUVIAL WEDGE**

Fault scarp degradation models suggest that scarp heights are typically twice the maximum thickness of the colluvial wedge if the slopes of offset beds are not too steep and the earthquake recurrence interval is not too short (10). Thus, as a first approximation the initial scarp height of the most recent event on the Oquirrh fault is assumed to be twice the maximum thickness of the colluvial wedge. Thickness measurements were made from X-Z slices of the 3-D tomogram at Y = 3.1 m, 4.6 m, and 6.1 m and the maximum (minimum) thickness was measured to be 3.5 m (2.9 m). This compares quite well with the thickness range of 2.6 m to 2.8 m estimated from the trenching study of Olig et al. (8).

**CALCULATING NET VERTICAL TECTONIC DISPLACEMENT**

Net vertical tectonic displacement is a measure of vertical slip across a fault caused by a surface-rupturing earthquake (11). Calculating the amount of vertical slip across a fault
consists of three estimates (1): 1) displacement on the main fault, 2) tilt angle of strata over a certain distance, and 3) vertical displacement on the antithetic fault. The net vertical tectonic displacement, $T_{net}$, can be calculated by the following equation:

$$T_{net} = T_m - [W\tan(\phi) + T_a].$$

As shown in Figure 8, $\phi$ is the tilt angle of shallow strata over the horizontal distance $W$, $T_m$ is the vertical displacement across the main fault, and $T_a$ is the vertical component of displacement across the antithetic fault. This equation shows that $T_{net}$ is the vertical displacement on the main fault adjusted for the effects of tilting and antithetic faulting. The amount of vertical displacement, $T_m$, on the main fault is calculated from measurements in the previous figure to be $T_m = 6.95$ m, assuming $T_m$ is twice the measured wedge thickness (8, 10).

The inflection point of tilting is estimated from the reflectivity image to be at an offset of 100 m in Figure 7, which implies tilting over a distance of $W = 51.5$ m. The amount of displacement across the antithetic fault is measured on horizon 1 and is $T_a = 1.3$ m. Plugging these values into equation 1 gives an estimate of $T_{net} = 2.04$ m for the net vertical tectonic displacement. In comparison, the trenching study of Olig et al. (8) gives a "best estimate" of 2.2 m for the net vertical tectonic displacement.
CALCULATING PALEOEARTHQUAKE
MAGNITUDE FROM DISPLACEMENT

The method of inferring paleoearthquake size from maximum displacement involves calculating the net vertical tectonic displacement $T_{net}$ and comparing it with measurements from historic earthquakes (1). Compilations of historic earthquakes (12, 13) yield empirical relationships relating maximum displacement ($T_{net}$) to moment magnitude (M) and surface rupture length (SRL) to moment magnitude. Wells and Coppersmith (13) give a regression equation for normal faults relating $T_{net}$ to the moment magnitude:

$$M = 6.61 + 0.71 \times \log(T_{net}),$$

(2)

where $T_{net}$ is given in meters. Plugging the value of $T_{net}$ into this equation yields a moment magnitude of 6.8 for the most recent earthquake on the Oquirrh fault. This compares well with the Olig et al. (8) estimate of a moment magnitude of 7.0.

SUMMARY

Our results demonstrate, for the first time, that seismic imaging methods can unambiguously delineate the 3-D shape and location of colluvial wedges. It also shows, for the first time, that information from reflectivity images and tomographic images can be combined to accurately estimate the size of prehistoric earthquakes. Thus, a new tool in paleoseismology is proposed where 3-D tomography combined with 2-D reflection imaging has the possibility
of providing cheaper, deeper and wider, but less resolved, images of fault systems than the intrusive excavation of trenches across faults. It might be possible to date the formation of the colluvial wedge by drilling through the identified wedge and using either a thermoluminescence or a radiocarbon dating technique (1) to date the core samples. Seismic imaging can add an extra dimension and a deeper perspective to the paleoseismic information gained from a 2-D trench excavation. When trench excavation is impractical, the seismic method may sometimes provide a viable alternative (14, 15).

The pdf or postscript copy of this manuscript is located at "http://utam.gg.utah.edu/schuster/science/index.html".

REFERENCES


6. Seismic Computerized Axial Tomography is an appropriate name for the 3-D imaging experiment because the colluvial wedge is penetrated by a dense set of rays with azimuthal angles over a 0° to 360° range.


15. We appreciate the support of Paul Dougan for providing a Dougan fellowship to Morey. We thank Ron Bruhn for his valuable advice about paleoseismology, and thank the IRIS organization for the use of their seismic recorder. We also thank Dr. R. Koehn, V.P. of Research at University of Utah, for the internal research grant that purchased 100
Hz phones and cables. And finally we thank the following people for their assistance in the field experiments: F. Meng, Y. Wang, J. Chen, Z. Liu, D. Sheley, G. Waite, E. Tartaras, H. Sun, D. Johnson, L. Xiang and D. Lynch.
FIGURE CAPTIONS

1. Depiction of sequence of earthquake events. (a) Cross section of layered earth, with rubble at the surface. (b) Eruption of normal fault earthquake, with rubble filling up the downthrown side of fault. This rubble fill forms a small colluvial wedge. (c) A short time later, a new layer forms on top of the rubble, preserving the shape of colluvial wedge. The thickness of a colluvial wedge is proportional to the fault displacement, which is proportional to earthquake magnitude. (d) The distance between adjacent colluvial wedges is proportional to the earthquake recurrence interval.

2. Depiction of dashed raypaths that originate from a seismic source and terminate at a geophone. The earth’s velocity model is reconstructed from first-arrival traveltimes measured from the recorded vibrations, where the seismic velocity in the rubble is assumed to be slower than the velocity of the surrounding alluvium.

3. Photograph of the Oquirrh Fault looking east towards the foothills of the Oquirrh Mountains just south of I-80. The shadowed linear feature represents the Oquirrh Fault scarp, and the rectangle denotes the 44.2x9.1 m² area of the seismic experiment adjacent to the trench excavated by the Utah Geological Survey.

4. Shot and receiver lines (solid lines) of the 3-D seismic experiment and relative elevation contours (dashed lines). Each geophone station was visited by a shot, there were 48 evenly-spaced geophone stations along each line with a station interval of 1 meter, and all geophones were effectively activated for each shot. The estimated intersection of the normal fault with the surface is denoted by the heavy solid line.
5. 3-D tomogram reconstructed from 83,570 traveltimes.

6. Comparison of the geologic gross-section (8) and the corresponding portion of the 3-D tomogram sliced at \( y = 3.1 \text{m} \). Notice the similarity in both the shape and location of the colluvial wedge in each figure.

7. (Top) Geologic section interpreted from trench log (8) and (bottom) corresponding stacked seismic section. Four horizons are interpreted, where the amount of dip on horizon 1 between the main fault and offset distance of 100 m defines the amount of tilt due to faulting. The layer offset of horizon 1 on the antithetic fault was also measured from this seismic section. The colluvial wedge is not well imaged, but the geometry of the shallow strata and the antithetic fault are well imaged. The data were collected with 100 Hz geophones.

8. Figure showing the components required for calculating net vertical tectonic displacement (\( T_{\text{net}} \)). The components are displacement (\( T_m \)), tilt displacement (\( T_t \)), the offset distance (\( W \)) to the inflection point, and vertical displacement on the antithetic fault (\( T_a \)).
Colluvial Wedges and Ancient Earthquakes

(a) Pre-Earthquake

(b) Earthquake

(c) 1000 years later

1. Colluvial Wedge
2. (Thickness $\propto$ Earthquake Magnitude)

(d) 10,000 years later

1. 2 Colluvial Wedges
2. (Separation $\propto$ Recurrence Interval)

Figure 1: Depiction of sequence of earthquake events. (a) Cross section of layered earth, with rubble at the surface. (b) Eruption of normal fault earthquake, with rubble filling up the downthrown side of fault. This rubble fill forms a small colluvial wedge. (c) A short time later, a new layer forms on top of the rubble, preserving the shape of colluvial wedge. The 2'-18' thickness of a colluvial wedge is proportional to the fault displacement, which is proportional to earthquake magnitude. (d) The distance between adjacent colluvial wedges is proportional to the earthquake recurrence interval.
Figure 2: Depiction of dashed raypaths that originate from a seismic source and terminate at a geophone. The earth’s velocity model is reconstructed from first-arrival traveltimes measured from the recorded vibrations, where the seismic velocity in the rubble is assumed to be slower than the velocity of the surrounding alluvium.
Figure 3: Photograph of the Oquirrh Fault looking east towards the foothills of the Oquirrh Mountains just south of I-80. The shadowed linear feature represents the Oquirrh Fault scarp, and the rectangle denotes the 145’x30’ seismic experiment area adjacent to the trench excavated by the Utah Geological Survey.
Figure 4: Shot and receiver lines (solid lines) of the 3-D seismic experiment and relative elevation contours (dashed lines). Each geophone station was visited by a shot, there were 48 evenly-spaced geophone stations along each line with a station interval of 1 meter, and all geophones were effectively activated for each shot. The estimated intersection of the normal fault with the surface is denoted by the heavy solid line.
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