CURRENT STATUS OF RESEARCH IN EARTHQUAKE GEOLOGY IN THE USA

McCALPIN, J.P., GEO-HAZ Consulting, Inc., 1221 Graves Ave., Estes Park, Colorado 80517 USA

Summary
In the past decade the study of earthquake geology in the USA has advanced in 10 areas, described below. Most of these advances involve newly-developed field techniques that permit collection of paleoseismic data, which in the past was not obtainable. Some techniques take advantage of new computer display and analysis software to interpret paleoseismic data.

Introduction

In this paper I briefly describe the 10 new techniques or advances in earthquake geology in the USA. For further information, please contact the investigators directly by e-mail.

1. Deeper and Longer Trenches

As earthquake geologists become more familiar with modern excavation equipment, they tend to excavate deeper and longer trenches across active faults than were dug in the 1970s and 1980s. Typical trench dimensions are evolving from the 1 m-wide, 3 m-deep, single slot configuration, to more complex benched cross-sections that may be 8-10 m wide at the surface, with 1.5 m-high benches stepping down to ultimate depths of 8-10 m. An example is the 8 m-wide, bench-and-slot design of the "megatrench" across the Wasatch fault zone (Utah); this trench exposed 24 m of vertical stratigraphic section as it transected an 18 m-high fault scarp (J.P. McCalpin,www.geohaz.com/geohaz).

Another trend is to custom-configure multiple trenches to mimic natural exposures. The five half-trenches excavated across the County Dump fault (Albuquerque, New Mexico) stepped down an eroded escarpment where the fault plane and colluvial wedge sequence was discontinuously exposed. The five trenches were spaced about 5-10 m apart horizontally, but were dug so the lowest stratigraphic layer exposed in the upper trench was exposed at the top of the next trench downslope (Fig. 1). In this manner the series of trenches exposed the fault plane and adjacent colluvial wedge of 17 vertical m (www.geohaz.com/geohaz)

Several recent trench studies have re-occupied the sites of smaller, shallower trenches dug in the 1970s-1980s, and have excavated much deeper, benched trenches to expose a longer paleoseismic history (J.P. McCalpin's 1999 megatrench on the Wasatch fault; T. Rockwell's [trockwel@geology.sdsu.edu] 1999 trench across the Garlock fault, California).

2. Boreholes As a Trench Substitute

In some urban areas digging a deep trench is impractical, given the surface width required and the area required to store the spoil dirt. In these cases boreholes can be used as a trench substitute to detect vertical displacements. In Los Angeles the Hollywood fault was studied in reconnaissance by J. Dolan (Univ. of S. Calif.; dolan@earth.usc.edu), who drilled 9 cm-diameter, 75 m-deep continuous cores in a 400 m-long transect across the fault zone; cores were spaced about 15 m apart. Once the zone of vertical deformation was identified, a second series of 9 cm-diameter cores was obtained on a 3 m spacing to further define the deformation zone. Then Dolan developed a trench-like exposure using a series of 9 0.7 m-diameter bucket auger boreholes. After the first auger hole was drilled, a geologist was lowered down the hole and mapped the walls. Then that first hole was backfilled with slurry concrete, and a second borehole was dug adjacent to it. Geologists then mapped this borehole, and the process was repeated in 7 additional boreholes until the entire fault zone had been mapped. Excavation costs were about US$2000 for each borehole, not counting the cost of the concrete slurry.

3. Computer Methods for Trench Log Display

With increasing trench widths it is easier to make photograph mosaics of the trench walls. The first step in making a mosaic is to photograph the walls in sections at a constant distance from the wall. A tubular framework named the "trench-o-matic" was developed by T. Fumal (USGS; tfumal@usgs.gov) to hold a camera perpendicular to the trench wall at a distance of 1 m. With a 20 mm lens on a 35 mm camera about 1 square meter of the wall can be photographed in each shot. Photographs taken with this framework will be at a constant scale, and if overlapped 30-50%, can be used to make a mosaic. The second step is to digitize the overlapping photographs (not necessary if a digital camera is used). The third step is to load the digitized photographs into computer software that can produce a seamless photo-mosaic (one such product is QuickStitch, sold by www.enroute.com).

The photomosaic can then be used in several ways. A common technique (courtesy of Tim Dawson; tdawson@geology.sdsu.edu is to take the photographs and print the photo-mosaic before the trench is logged, but after the control grid is marked on the walls (via vertical and horizontal string lines, or other method). The geologist then takes the photo-mosaic into the trench and draws the geologic contacts directly onto the mosaic. Later he returns to the office and digitizes the geologic contacts into lines or polygons. These vector lines/polygons will be registered to the photo-mosaic, and the latter contains the control grid for scale. For later display and printing, the photo-mosaic can be displayed as a background bitmap layer while the vector lines are displayed in overlay mode.

4. Computer-Assisted Retrodeformation Analysis of Trench Logs

If the trench log is digitized into vector format (lines and polygons) the log can be "retrodeformed" by computer graphics software. The retrodeformation process involves sequentially removing the youngest depositional layers and deformation effects from the trench log to estimate what the exposure would have looked like at previous stages in its evolution. During retrodeformation one first removes post-faulting deposits (such as colluvial wedges) and restores any materials removed by post-fault erosion. Then one reverses the vertical displacement across the fault plane in the most recent faulting event (MRE), to bring the hanging wall and footwall into their pre-MRE geometry. This process is then repeated for successively older deposits and displacement events, as far back in time as possible.

The graphical procedure is simplified if the fault plane(s) portrayed on the trench log are simplified into straight lines, otherwise gaps will open up along the fault plane when the displacements are reversed.

Using computer graphics software on a vectorized trench log simplifies removal of post-faulting deposits from the log, restoring of inter-faulting erosion, reversal of displacement across faults, and back-rotating deposits on the log that were rotated

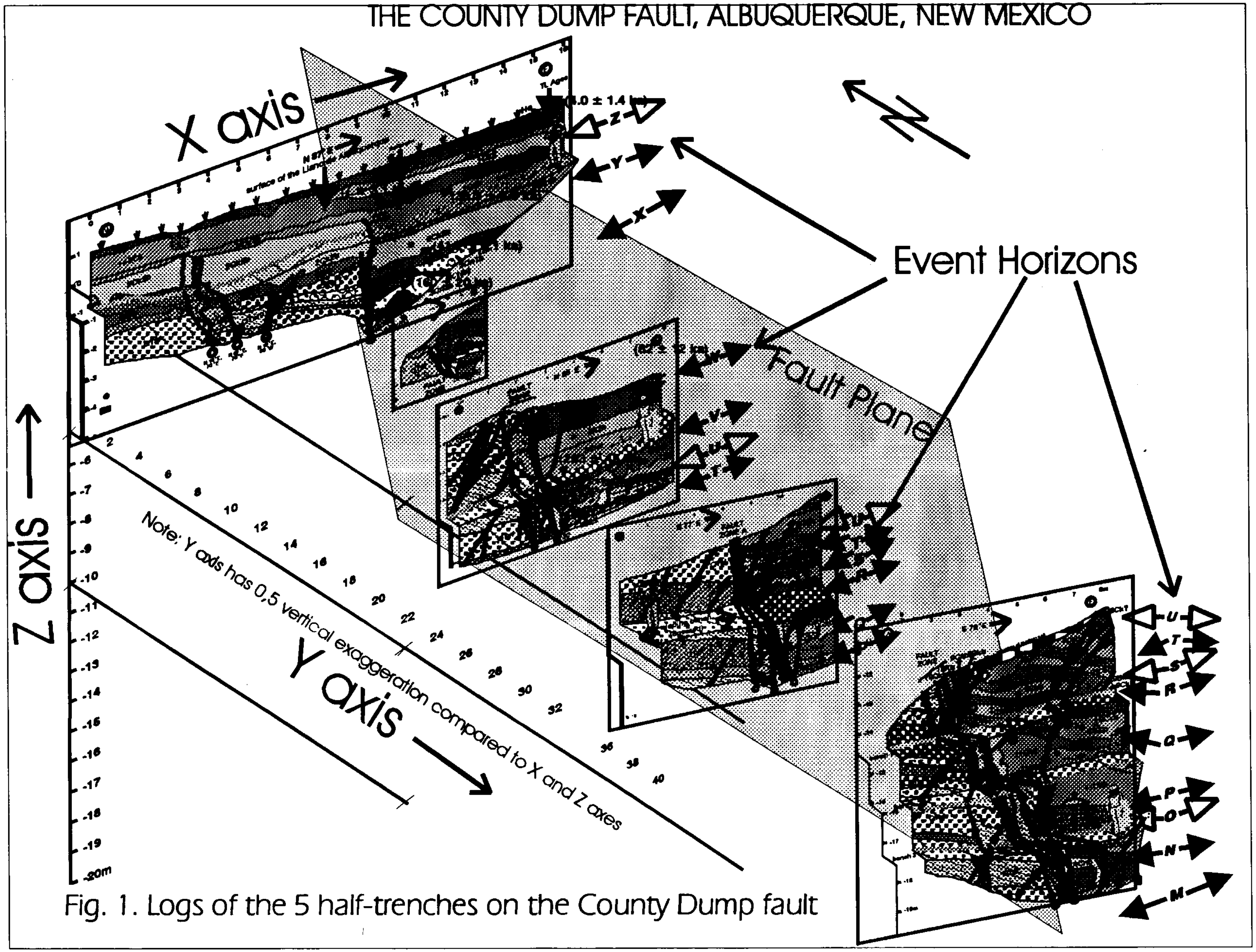

Fig. 1. Logs of the 5 half-trenches on the County Dump fault

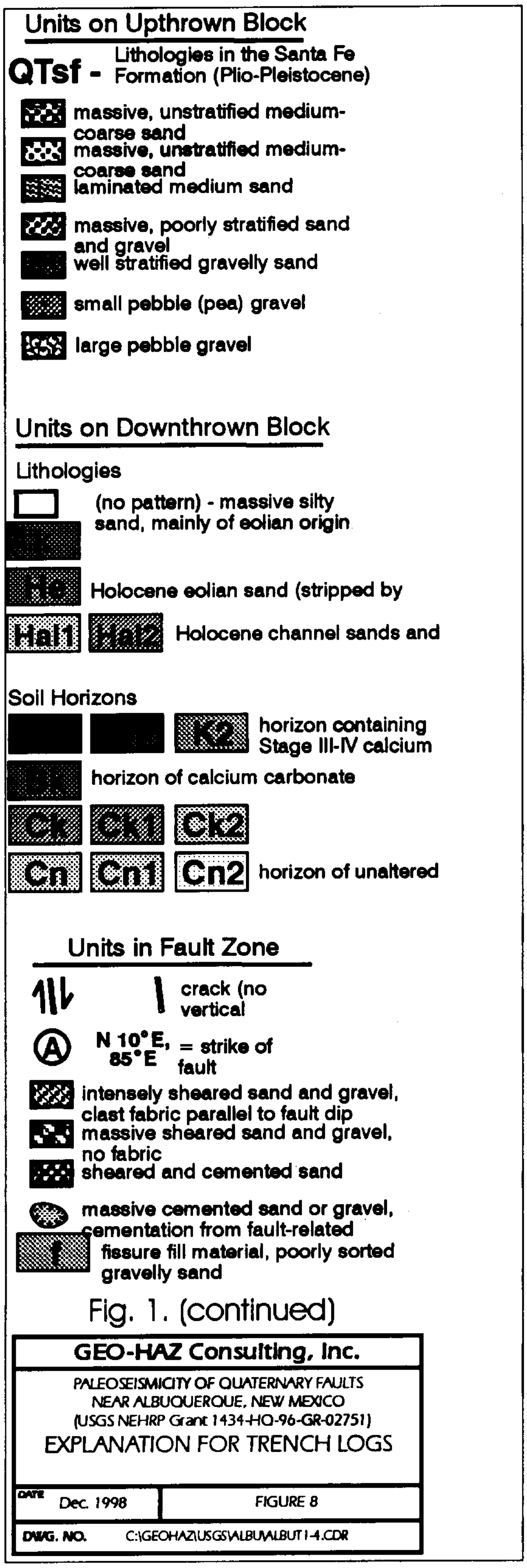

Fig. 1. (continued)

during faulting. Sometimes going step-by-step through the retrodeformation process will force the geologist to change his mind about the number of faulting events, their relative timing, and their displacement. I strongly suggest that every trench log be retrodeformed before the geologist writes his final interpretation of the trench exposure.

5. Geophysics in the Near-Surface Environment

Several land-based geophysical methods have been refined to detect faults and fault-related sediments in the shallow subsurface. For example, G. Schuster (Univ. of Utah; schuster@mines.utah.edu) performed seismic tomography on a scarp of the Oquirrh fault west of Salt Lake City, Utah. This fault scarp had been trenched in 1992 (see 1994 paper in Geomorphology, v. 10, p. 285-315) and found to be the result of two faulting events, one prior to the transgression of Lake Bonneville over this site (ca. 20-26 ka) and one about 7 ka. The tomograms were produced by a 60 by 60 geophone array using seismic refraction techniques.

6. Offshore Paleoseismology

Marine and lake studies in the past several years have used high-resolution seismic reflection surveys to image submerged faults. In some cases these studies, if supported by coring studies, can yield paleoseismic data comparable to that of on-shore trench studies.

D. Dinter (Univ. of Utah; dadinter@mines.utah.edu) acquired 325 km of high-resolution seismic lines which crossed the East Great Salt Lake fault 31 times. Water depths were 2-10 m and depth penetration into bottom sediments was 15-20 m at 2-7 kHz. This previously-unknown fault displays evidence for 3 faulting events since 12-15 ka.

7. Rapid C-14 AMS Dating

Several radiocarbon dating laboratories are now offering 24 hour to 72 hour delivery service for conventional C-14 and AMS dates. For example, Beta Analytic Inc. (www.radiocarbon.com) offers "Time Guide" conventional C-14 dates in 2-3 business days. Even quicker turn-around time was provided by the Lawrence Livermore (California) radiocarbon laboratory to the Bay Area Paleoseismic Experiment (BAPEX) of USGS in the San Francisco Bay Region, California. Radiocarbon samples from a trench across the Hayward fault were sent by courier to the Livermore laboratory, and AMS radiocarbon dates were reported back to the trench loggers within 24 hours (dschwartz@usgs.gov).

This opportunity for trench loggers to receive their radiocarbon ages while the trench is still open has profound implications for trench investigations. Now, the trench loggers can know the absolute age of deposits in the trench while they are still working in the trench, rather than only receiving the dates weeks after the trench has been backfilled. Hypotheses about contemporaneity of deposits and deformation events can be tested, particularly where deposits are not in physical contact with each other. A common need of contemporaneity testing is to determine whether multiple fault strands exposed in a trench moved at the same time (one paleoearthquake), or represent multiple paleoearthquakes. This determination often cannot be made from cross-cutting relationships because the faults a parallel and widely spaced. With the advent of 1-3 day dating services, the paleoearthquake chronology can now be much more firmly established before the trench is backfilled.

8. Quaternary Faulting in Stable Continental Regions

Faults with late Quaternary displacement continue to be found in the "Stable Continental Regions" (SCR) of the USA. Typically these are reverse faults with low slip rates. In Colorado, A.J. Crone (crone@usgs.gov) documented two surface-faulting events on the Meers fault (Oklahoma) at 1.1-1.2 ka and 2.9-3.4 ka, leading to a recurrence time of 1.7-2.3 kyr between events. However, the previous faulting event must be older than 130 ka, implying a minimum recurrence interval of 127 kyr. This very large variation in recurrence intervals may be typical of SCR faults.

Crone and M.N. Machette (machette@usgs.gov) documented a 7-8 m-high Quaternary fault scarp on the 44 km-long Cheraw fault in southeastern Colorado. Their trench recorded two latest Pleistocene faulting events (<30 ka) and one Holocene event at <7.7 ka.

These USGS workers speculate that the current inventory of potentially seismogenic faults in SCRs is incomplete, because: 1) fault slip rates are very low compared to the rates of erosion, so fault scarps are poorly preserved, and 2) much of the north-central USA is covered by continental glacier deposits ca. 15,000 years old, so prior faulting cannot be detected.

9. Computer Analysis of Digital Topographic Data

The current trend in geomorphology of analyzing digital elevation models (DEMs) has applications for earthquake geology, particularly in areas such as SCRs where the surface expression of faulting is subtle. The overall goal of DEM topographic analysis is to identify geomorphic anomalies that can be related to low-slip-rate faults or folds. The most successful application of these techniques has been in areas of blind thrusts, as described in the next section.

10. Paleoseismic Analysis of Blind Thrusts

Blind thrusts have been studied in the midcontinent USA and in California. In the New Madrid Seismic Zone of Missouri, low-slip-rate faulting and folding has occurred in the late Quaternary contemporaneous with fluvial deposition in the Mississippi River Valley. The key neotectonic landforms analyzed by K. Mueller (Univ. of Colorado; karl@emarc.colorado.edu) are the Tiptonville Dome (2 km by 3 km by 37 m high) and the Reelfoot Monocline. A trench across the Reelfoot Monocline reveals three discrete zones of steep dip, 12-15 m wide, that are interpreted as kink bands created by the underlying blind thrust. The structural solutions for underlying fault geometry use the widths of these kink-bands (fault-bend model) and the structural relief (fault-propagation model) to define respective slip rates of 6.1+/-0.7 and 4.8+/-0.2 mm/yr over the past 2.3 ka.

Farther south in the Mississippi Valley DEM analysis revealed a parallel alignment of tributary streams and a persistent valley asymmetry that could be interpreted as the result of reverse faulting. Subsequent field investigations discovered previously-unrecognized faults in roadcut exposures that were consistent with the stream pattern. These faults offset the Peoria Loess (age ca. 15 ka) and are thus late Quaternary in age.

In southern California K. Mueller has studied the San Joaquin Hills and Wheeler Ridge anticlines over blind thrusts, and has developed models relating structural development to geomorphology. These growing anticlines have been notched on one or both sides by Quaternary marine terraces ranging in age from 83 ka to 1.3 Ma. The geometry and preservation of marine terraces on a growing anticline differ for anticlines created by: 1) thrust ramp/fault-bend deformation, 2) wedge-thrust/fault-bend deformation, and 3) fault-propagation folding. Thus, geomorphology gives clues to the style of underlying deformation, and the ages of the deformed marine terraces can thus be translated into slip rates on the blind thrust. This exciting, in-progress work is a good example of applying traditional structural geologic concepts with geomorphology to solve active tectonic problems.

11. Controversy Over Tectonic Faulting Versus Liquefaction-Induced Faulting

In two recent investigations there has been heated controversy over small-scale faulting observed in trench exposures. In Salt Lake City, Utah, the basement excavation for a large building exposed a 50 m-wide zone of normal faults, including at least 2 grabens. Vertical displacement on individual graben-bounding faults was as large as 2 m, but the net vertical displacement across the entire deformation zone was negligible. One group of geologists (rshlemon@jps.net) argued that the graben represented tectonic faulting, while another group (tlyoud@byu.edu) argued that the grabens represented the head of a lateral spread landslide caused by liquefaction.

This distinction is critical due to the way geologic hazard regulations are written in the USA. If the normal faulting was tectonic, then the fault zone would be zoned as an active fault, and building could not be constructed, because regulations prohibit building astride active fault traces. In contrast, if the normal faulting was caused by lateral spreading (a type of landslide), the building could be constructed, because there are no regulations prohibiting construction across landslide boundaries. In the Salt Lake City case the landslide proponents won and the building will be built.

A similar case occurred on the Malibu fault in southern California. Trenching investigations in the 1970s interpreted small faults displacing marine terrace sediments as tectonic. Larger trenches excavated in 1999 documented that the faulting was caused by liquefaction of the marine terrace sands (Mzorba@earthconsultants.com). This liquefaction could have been caused by earthquakes originating on many possible faults in the area, not merely on the Malibu fault. Thus, the active status of the Malibu fault is now in question, with all the regulatory constraints that such status implies.

12. The United States Map of Major Active Faults

This project is a part of International Lithosphere Program Project II-2, and seeks to create a computer database of major active faults in the USA. Once completed, the digital maps and linked databases will provide easily-accessible information on active faults, for use in applied studies (seismic hazards, engineering geology) as well as for research studies into neotectonic frameworks.

Conclusions

Recent progress in earthquake geology has come from adapting techniques from other technical fields, such as excavation technology, C-14 dating, and computer graphics software. This trend suggests that the field is maturing and is no longer as self-referential as it was in the 1970s and 1980s.

Acknowledgments

I thank all persons whose e-mail addresses are listed herein for their assistance in compiling this progress report.