50 Years of Paleoseismology:

The Science and the Business

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The modern era of Paleoseismology arguably began 50 years ago, shortly after the 1971 San Fernando, California earthquake (M6.6). This was the nation's most damaging urban earthquake since the 1933 Long Beach earthquake (M6.4), and the first to occur after active fault studies for nuclear power plants had begun in the mid-1960s (e.g. Schlocker et al., 1963).

Paleoseismology, the Science

Paleoseismic studies in the 1970s studied deformation along the traces of known faults, some of which had experienced historic surface ruptures. These "tectonic geomorphology" studies did not involve trenching the fault trace (which came later), but nevertheless yielded the first crude estimates of active fault parameters needed for seismic hazard analysis (e.g. Wallace, 1970). USGS continued this geomorphic emphasis up to 1977, when the National Earthquake Hazards Reduction Program (NEHRP) was created. In addition to the USGS Internal Program, the NEHRP External program for academics and consultants was more applied, relying more on trenching and studying fault hazards in hitherto unstudied (or under-studied) geographic areas. External studies discovered many previously unknown Holocene-active faults, which paved the way for the Quaternary Fault and Fold Database of the USA. http://bit.ly/earthquakehazards

Because Paleoseismology developed during the past 50 years, we can observe how the field underwent a stairstep evolution of rapid advances (triggered by new techniques), separated by plateaus in which the new techniques were applied to studies over large geographic areas (Figure 1).

The 1970s fault-centric nature of paleoseismic studies has continued to this day and has advantages and disadvantages. Such "primary" studies do yield the seismic source parameters for individual faults (surface rupture length, displacement per event, slip rate, recurrence interval, maximum/characteristic magnitude) needed for seismic hazard analysis (SHA), which is a forward model (from cause to effect). The weakness of the method is if active faults exist in the studied area that are not known, the seismic hazards are underestimated. This is particularly true in areas of blind faulting, or where the characteristic earthquake magnitude is at or below the threshold for surface rupture (M~6). The alternative approach is to study a site's record of strong ground shaking directly, as preserved by evidence of prehistoric liquefaction and/or other ground failures (landslides, lateral spreads, toppled rocks, etc.). This "secondary" approach is not affected by the problem of unknown active faults. It does have three weaknesses, however. First, most sites are not particularly susceptible to liquefaction or ground failure. Second, the size of observed liquefaction/ground failure features, based on historic observations, does not scale linearly with the strength of ground shaking. Third, liquefaction and ground failure can be triggered by nonseismic means. As a result, current predictions of probabilistic fault displacement hazards (PFDHA) and probabilistic ground motions (PSHA) are built from fault-specific evidence, with usually no regard for the presence or absence of secondary evidence at (or near) the site, even used as a reality check on the forward model results.

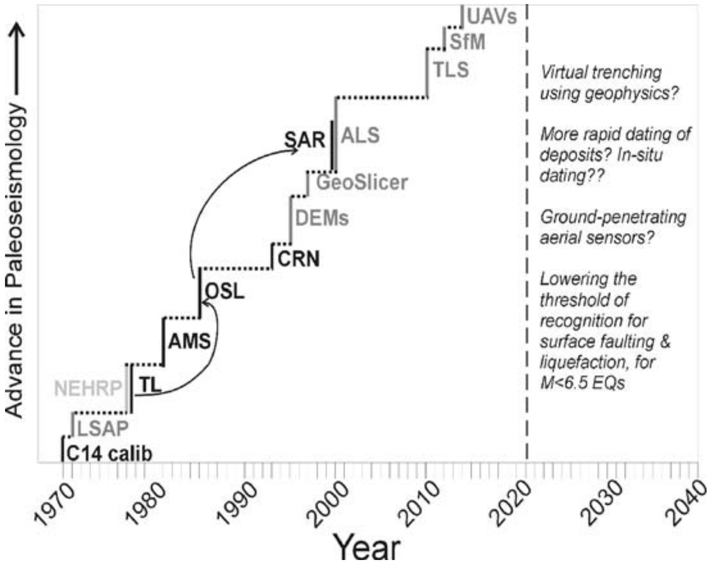

Figure 1. *New techniques (vertical lines) that have advanced Paleoseismology; black, dating methods; medium gray, remote sensing methods; light gray, institutional changes. Impact on the science is reflected by the height of vertical lines (in our subjective viewpoint). Curved arrows show how later advances in a single technique (luminescence dating) have superseded earlier methods. C-14 calib, calendar-correction of radiocarbon ages; LSAP, Low-Sun-Angle Photography; TL, thermoluminescence dating; AMS, Accelerator Mass Spectrometry radiocarbon dating; OSL, Optically-Stimulated Luminescence dating; CRN, Cosmogenic Radionuclide dating; Digital Elevation Models; SAR, single aliquot or single grain luminescence dating; ALS, Airborne Laser Scanning (lidar); TLS, terrestrial lidar; SfM, structure from motions DEMs; UAVs, unmanned aerial vehicles (drones).*

What About Interpretive Paradigms?

A new interpretive paradigm (e.g., plate tectonics) can have a bigger scientific impact than any one new field or laboratory technique. New paradigms often arise from new types of data, which themselves became possible from a new technique (e.g., Figure 1). A recent example is surface rupture patterns and their prediction by PFDHA. At present, predictive relationships for surface rupture are based solely on empirical data (i.e., no underlying physical or kinematic model). Not surprisingly, predicted outputs carry high uncertainty. The new remote sensing techniques mentioned in Figure 1 (ALS, TLS, SfM, UAVs) permit mapping every tiny rupture trace, resulting in hundreds to thousands of rupture traces defined, and point displacements measured. For example, the Norcia, Italy, rupture of 2016 yielded 5,400 point measurements of displacement, most on distributed faults. Such data densities were not possible previously but are statistically robust enough to support development and testing of physical/kinematic models of principal and distributed faulting. For example, fault rupture may be partly controlled by depth to bedrock or by the rheology of the surface materials, neither of which are used in present PFDHA models. Underpinning PFDHA with a physical model should, in theory, decrease the uncertainty in predicted fault trace length, location, and displacement, because data points that clearly contradict the physical model can be deleted. But will the final uncertainty become small enough that engineering geologists and their owner/clients will rely upon them for site specific design and hazard mitigation? This is where the academic aspirations run into the practical business realities of cost-benefit analysis.

Science Outlook for the Future

What are the most likely near-term scientific advances? Based on trends of the first 50 years, advances will probably occur in dating methods, remote sensing, and perhaps geophysics:

1) Rapid Dating (within a few days), so dates can be known before the paleoseismic trench must be backfilled. This would prevent the syndrome of “Oh, if I would have known that faulted bed was Holocene, I would have….” Commercial labs currently offer “rush” AMS radiocarbon dating within one week, but for luminescence dating even “rush” dating takes months. Few practitioners can get permission to leave a trench open for months, so a more rapid dating turnaround would help with trench interpretation.

2) “Virtual Trenching” via shallow geophysics. Twenty years ago, attempts were made to log stratigraphy and structure beneath normal fault scarps using P- and S-wave seismic tomography, which was touted as “seismic trenching” (e.g., Sheley et al., 2003). However, the tomograms could not distinguish thin or small deposits or displacements, which were easily visible on the log made by conventional trench logging. This research thread has stalled in the past decade, but should be taken up again, because as urban fault traces become totally developed, traditional trenching is no longer possible. One possibility to maintain high resolution with depth is to augment surface geophysical surveys with downhole surveys, which can use wave-guide principles to trace subsurface deposits between boreholes. This could potentially increase the depth of detailed fault-zone imaging to tens of meters, regardless of depth to water table.

3) New remote sensing techniques that image the shallow subsurface. Just as lidar penetrates surface vegetation to reveal the bare-earth topography, a useful advance would be an aerial sensor that penetrates the upper few meters of the subsurface and can measure its material properties (density, moisture, dielectric properties). Such a sensor could directly image young, low-density materials deposited in topographic traps (grabens, ramps) in active fault zones, even where the traps have no surface expression today because they are filled with sediment. These are good trenching targets.

4) Refined methods to identify and analyze the paleoseismic signature of M<6 earthquakes. Californians have been waiting 110 years for a repeat of an M8 earthquake on the San Andreas. But for every M8 earthquake in a seismic cycle, there will be 10 M7s and 100 M 6s (think of San Fernando M6.6; Whittier Narrows, M6.0; Coalinga M6.2; Loma Prieta, M6.9; Northridge, M6.7; South Napa, M6.0). The cumulative damage from 100 such M6s will be as large or larger than a single M8. But the evidence is much smaller and harder to find.

5) Increased usage of secondary paleoseismic evidence (liquefaction, ground failures) to provide reality checks in PSHA (e.g., Fan et al., 2019).

Paleoseismology, the Business

Business needs for paleoseismic studies are separate from and independent of the science advances, which take place in academia and in government agencies (public policies based on new knowledge and experiences). The business need (or opportunity for paleoseismologists) is thereby generated by these public policies and regulations, while the engineering geologist’s ability to comply and solve their client’s problems is, to a large degree, facilitated by the scientific advances of the academic paleoseismology community. Unfortunately, these advances are often under the radar of the practicing engineering geology practitioner, or to quote Dr. Kerry Sieh in 2000, “the state of the knowledge is at least 10 years ahead of the actual use of that knowledge” (Yeats and Gath, 2005). This lag time led to the development of technical specialists in the applied paleoseismology discipline, perhaps starting as far back as Dr. Roy Shlemon and the fledgling California nuclear power industry in the mid-1970s.

Historically Dominant Market Sectors

Paleoseismic projects range over several market sectors: **Water-related** (Dams, Aqueducts, Tunnels); **Energy-related** (power plants, including nuclear; extraction sites, such as offshore drilling platforms; pipelines and terminals, such as LNG terminals); **Waste disposal-related** (high-level and low-level nuclear waste repositories; landfills); **Transportation** (highways, railroads); **Land development-related** (residential, commercial). In the 1960s–70s nuclear projects dominated the market at large scales, whereas in 1973 California’s *Alquist-Priolo Fault Zoning Act* required small-scale “paleoseismic” studies for residential and commercial land-use changes. The smaller budgets of the residential studies were offset by their sheer numbers (thousands), so cumulatively they were as important as the large-scale projects for critical facilities.

Paleoseismic Studies Driven by Regulations

Engineering geologists were aware of the fault rupture hazard before there was a scientific method to quantify that hazard sufficient for risk reduction. Indeed, even the Alquist-Priolo Act was silent on the possibility of quantitative paleoseismology, requiring instead the strict avoidance (setback zone) from any Holocene-age faults. The Act was silent because the science did not yet exist from which to understand prior fault rupture timing, displacement magnitude, or even its spatial locations. The only mitigation permitted by law in California was, and unfortunately still is, strict structural avoidance. Since 1973 therefore, even though huge advances in paleoseismology have been made within the academic community, most engineering geologists in California have little need for them. Is this sediment layer or buried paleosol (soil) horizon Pleistocene or Holocene, and is it faulted or not? Period.

But large engineering projects are not necessarily subject to the limitations within the Alquist-Priolo Act, and structural mitigation for fault rupture displacement does look to paleoseismology to help answer design questions such as displacement magnitudes, kinematics, most recent event and knowledge of recurrence intervals. Of course, all of these parameters are unlikely to be obtained from any single study site, so it is also necessary for the practitioner to be able to define the uncertainties in a manner that can be used by the design engineer and understood by the project's reviewers. Specific examples of these kinds of projects involve cutting the U.C. Berkeley football stadium in half to accommodate the Hayward fault's current creep rate and future earthquake rupture, PG&E's ongoing natural gas pipeline risk studies at fault crossings, and LA Metro's fault rupture mitigation program for its subway tunnels.

Business Prospects for the Future

Predicting business trends in paleoseismology is even more uncertain than predicting its scientific advances. The current trending concerns are described below.

Market Sectors

Many countries have recently pledged to reduce or eliminate fossil fuels as a source of energy in favor of renewable energy, within the next decade or two. If this occurs (it will be expensive), it will reduce paleoseismic projects from the fossil fuel sector, such as oil and gas pipelines, offshore drilling rigs, and possibly nuclear power plants and waste repositories (after all, uranium is not a renewable energy source). The transition to renewable energy for stationary facilities (residential, commercial, industrial) and transportation (autos, Elon Musk's Hyperloop, long-haul trucks, high-speed trains, airplanes) is basically a transition to electrical energy. Today electricity is generated by fossil-fuel powered, industrial-scale plants (=critical facilities), many of which require geologic hazard studies. In contrast, much future renewable electricity will be generated at widely dispersed points of use, which will not require geologic hazard studies. In the transportation sector, the increased speed of electrical vehicles such as high-speed trains may trigger a requirement for studying small ground movements, including tectonic ones. The amount of allowable track deflection for a 200–300-mph electric train is much smaller than for a 55-mph Amtrak coach.

The past 20 years has been a drought cycle in much of the western United States, and with the westward population shift from COVID-19, metro areas of the West are scrambling for new water supplies. At this time, Lakes Mead and Powell on the Colorado River contain only 37% and 34% of capacity, respectively. Lower levels will trigger a Lower Basin "water shortage condition," resulting in decreased water allotments to Arizona, Nevada, and Mexico. This will spur new dam projects, pipelines, and aqueducts in earthquake country.

Regulatory Changes

California geologists hope to someday be able to use their paleoseismic tools and expertise under a modernized Alquist-Priolo Act which opens up the mitigation alternatives to more than just avoidance. In the almost 50 years since its passage, its interpretation by regulators and state geologists has become increasingly prescriptive (Gath, 2015), while engineering mitigation of ground deformation has become increasingly performance and risk based, relying on huge increases in computer power for modeling, mechanical testing, materials science, and learning from earthquake studies to improve their professional practice (Committee, 2003). If engineering geologists were able to apply the current knowledge base in paleoseismology techniques to their projects the increase in knowledge for all of California's faults would increase exponentially because now there would be hundreds if not thousands of projects per year wherein rupture recurrence, kinematics, and magnitudes would be built into the investigation plan and budget as it would finally be important for design and engineering mitigation. If the displacements exceed the capacity for mitigation, avoidance is still an option, but until engineers are allowed to try, paleoseismic-level geologic investigations cannot be defended as standard of care.

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About the Authors

James McCalpin, BA 1972, University of Texas; MS 1975, University of Colorado; PhD 1981, Colorado School Mines, has worked in applied geomorphology, geohazards, and paleoseismology since 1976. He was County Geologist of Jefferson County (CO) in 1981–82, then taught geomorphology and engineering geology 1982–91 at Utah State University. Dr. McCalpin founded GEO-HAZ Consulting, Inc. in 1991 and has since performed nearly 200 consulting projects for clients worldwide. He has authored more than 160 papers in refereed journals and proceedings, 13 published geologic maps, and >130 consulting reports on geohazards for clients. His 1996 book *Paleoseismology* (Elsevier Publishing) won the AEG Holdredge (1999) and GSA Burwell (2000) awards. *Paleosesismology 2nd Edition* has been published in English (2009), Russian (2011), and Chinese (2020).

Eldon Gath, Founder and President of Earth Consultants International of Santa Ana, California, is a Past-President and Life Member of AEG. He served on the AEG Board of Directors from 1990–98 and 2016–19, was the 2014–15 Jahns Lecturer, and granted the Floyd T. Johnston and E.B. Burwell awards. He has served on numerous technical committees and advisory boards for the US Geological Survey, National Research Council, Southern California Earthquake Center, State of California, IAEG, EERI, and others. Eldon has worked on projects throughout California and other western states, and in a dozen countries as diverse as Japan, Papua New Guinea, Panama, and Turkey. His projects have included gas storage fields, oil field redevelopment, city and county hazard management plans, pipelines, canals, dams, tunnels, and hundreds of “typical” engineering geology studies for development planning, design, and construction.

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