Changing Direction in Paleoseismology: Where Are Faults In Their Current Seismic Cycle?

JAMES P. MCCALPIN, GEO-HAZ Consulting, P.O. Box 837, Crestone CO 81131 (mccalpin@geohaz.com)

ABSTRACT

In the past 10 years the world has experienced devastating earthquakes that did not occur on the faults with the fastest slip rates in the world, nor with the highest historic seismicity. The Bhuj (2001), Bam (2003), Kashmir (2005), Sichuan (2008), and Port-au-Prince (2010) earthquakes occurred on faults with low-to-moderate slip rates and low-to-nonexistent historic seismicity. But the faults all have one thing in common: they had reached the end of their seismic cycle of characteristic earthquakes. In addition, global earthquake deaths per decade have not decreased in the past century, a period than spans the rise and development of paleoseismology. Thus it can be argued that all our paleoseismic work has not reduced either seismic hazard or risk, and earthquakes such as the five mentioned above can be offered as proof of this. We cannot expect future confidence in, or funding for, paleoseismology if this lack of performance continues.

The above situation brings up a relevant question for paleoseismology; do we know the position of all Quaternary faults within their current seismic cycle? Can we identify which faults are early in their cycle, late in their cycle, or even perhaps "overdue" for a characteristic earthquake? That is, is the elapsed time since their most recent earthquake (MRE) greater than their mean recurrence interval? Or is the accumulated strain since the MRE greater than their mean displacement-per-event? If either of these conditions exist on a given fault, it should be ranked high priority for further detailed study.

What the above discussion suggests is that some paleoseismic parameters collected in the past, such as magnitude of the characteristic earthquake and its supporting data (e.g. fault length), are less critical to seismic hazard analysis than the ratios mentioned above. Let's change direction in paleoseismology, before our science is labeled useless.

INTRODUCTION TO THE PROBLEM

In the past 10 years the world has experienced the following devastating earthquakes:
2001 in Bhuj, India (20,023 dead)
2003 in Bam, Iran (31,000 dead)
2004 in Sumatra, Indonesia (>250,000 dead from tsunamis accompanying the earthquake)
2005 in Kashmir, Pakistan (80,361 dead)
2008 in Sichuan province, China (70,000 dead)
2010 in Port-Au-Prince, Haiti (316,000 dead)
Source: U.S. National Earthquake Information Center.

These earthquakes did not occur on the faults with the fastest slip rates in the world, nor the highest historic seismicity. The Bhuj, Bam, Kashmir, and Sichuan earthquakes occurred on faults with relatively low slip rates and low to nonexistent historic seismicity. This brings up a relevant question for seismic hazards in the USA; do we know the position of all our Quaternary faults within their current seismic cycle? Which faults are early in their cycle, late in their cycle, or even perhaps "overdue"? That is, is the elapsed time since their most recent event (MRE) greater than their mean recurrence interval? Or is their accumulated slip since the MRE greater than their mean displacement-per-event? If either of these conditions exist on a given fault, it should be ranked high priority for further detailed study, regardless of its slip rate. This concept was validated in 2008 in Nevada:

> *"A 7.0 earthquake along a known fault in the Frenchman Mountain area just east of Las Vegas would not only kill about 2,300 people, but also cause an estimated $25 billion in property damage, wreck 60,000 buildings and put 8,100 people in the hospital, he* [State Geologist Jonathan Price] *said. Of course, the chances of such an earthquake occurring in the next 50 years are less than 0.5 percent, according to Price.* But then Wells, in northeastern Nevada, had even less of a chance of experiencing an earthquake than Las Vegas. And on Feb. 21, 2008, a 6.0 magnitude earthquake rocked Wells and caused $9 million in damage."* Interview with Jon Price, 2009
>
> * assuming that the fault has no memory

THE FAILURE OF PALEOSEISMLOGY

The field of Paleoseismology was "invented" in the 1960s to extend the earthquake record into prehistoric time, to improve seismic hazard analysis (SHA). But after 40 years, we need to know:

-- have paleoseismic investigations really improved SHA?
-- have paleoseismic investigations decreased casualties from earthquakes?
-- If not, what should we do?

After 40 years of paleoseismic studies (1969-2009), still nearly 770,000 people died from earthquakes in the decade (2000-2010), the largest death toll in the past 11 decades. Why wasn't this prevented by modern science?

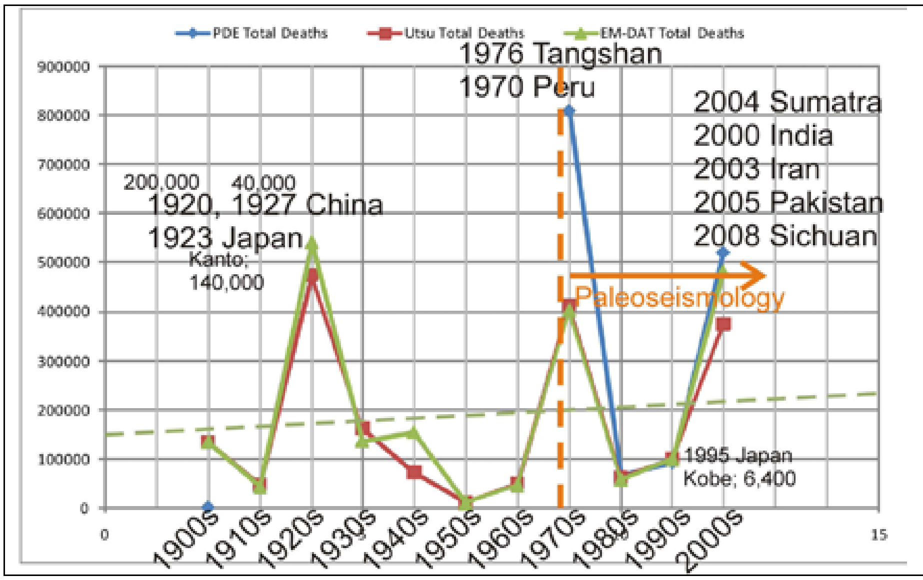

Figure 1. Worldwide earthquake deaths per decade since 1900. PDE, Preliminary Determination of Epicenters; Utsu, 2002; EM-DAT, Emergency Events Database (CRED, 2011).

Let's look at the killer earthquakes:

2010 Port-Au-Prince, Haiti; 12-JAN-2010; 316,000 dead; M7.0 earthquake on a blind oblique thrust fault associated with the Enriquillo-Plantain Garden fault (Hayes et al, 2010), one of two right-lateral faults comprising the plate boundary between the Caribbean plate and North

American plate. A 2007 earthquake hazard study by DeMets and Wiggins-Grandison (2007) noted that the Enriquillo-Plantain Garden fault zone could be at the end of its seismic cycle, based on the value of accumulated strain (GPS strain rate *times* the elapsed time). Mann et al (2008) presented a hazard assessment of the Enriquillo-Plantain Garden fault system to the 18th Caribbean Geologic Conference in March 2008, noting the large accumulated strain; the team recommended "high priority" historical geologic rupture studies, as the fault was fully locked and had recorded few earthquakes in the preceding 40 years.

The thrust component and lack of surface rupture of the 2010 earthquake imply that: (1) this earthquake was similar to the 1989 Loma Prieta earthquake “associated” with the San Andreas fault zone (Wells, 2004), and (2) the 2010 earthquake did not release a significant amount of the accumulated right-lateral strain on the main Enriquillo-Plantain Garden fault. CONCLUSION: No paleoseismic studies had been performed on the Enriquillo-Plantain Garden fault, even though it was a plate boundary fault with a slip rate of 6-8 mm/yr, going through a major urban area. The first study was done after the earthquake (Prentice and others, 2010). However, even if there had been studies of the fault, they might have failed to detect the subtle evidence of the associated, short thrust fault that ruptured in 2010, just as USGS was “fooled” in 1989 about the nature of the Loma Prieta earthquake.

2008 Sichuan (Wenchuan); 12-May-2008; 69,000 dead; M7.9 earthquake on the Longmenshan Fault, a poorly-expressed reverse fault with scarps at foot of steep range front. The range front is a major tectonic boundary between the eastern Tibetan Plateau and the Sichuan Basin (Figure 2). Millennia of cultivation had obscured these low scarps. A M7.5 earthquake in this same area in 1933 killed 9300 people. The first paleoseismic study of the fault was published in July 2007, less than a year before the earthquake (Densmore and others, 2007). That study deduced a fault slip rate of ~1 mm/yr and called the fault a “source of significant seismic hazard.” CONCLUSION: the failure here was not in the paleoseismic study itself, but in the long delay in studying this particular fault.

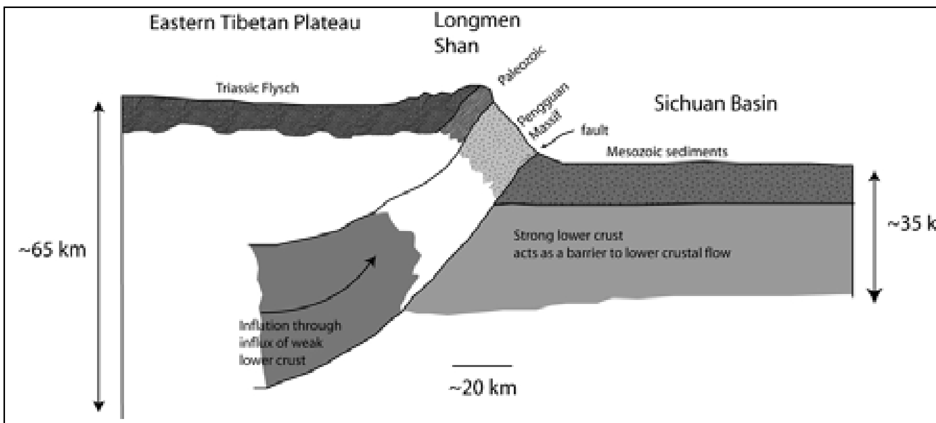

Figure 2. Schematic cross-section through the Longmenshan fault (labeled “fault” at ground surface), Sichuan, China. Sense of slip is interpreted to be primarily right-lateral with a smaller thrust component. From http://quake.mit.edu/~changli/wenchuan.html

2005 Pakistan; 8-OCT-2005; 87,000 dead; a M7.6 earthquake on a previously mapped active reverse fault (Muzaffarabad fault; Figure 3) at the base of steep range front in the western part of the Himalayan collisional plate boundary. According to Bilham and others (2001), an earthquake in this part of the plate boundary had “long been considered overdue” by tectonic experts, based

merely on the elapsed time since the last major earthquake, and the accumulated strain since then (based on geodetic measurements of plate convergence). The fault displayed 4-7 m coseismic displacements along strike. There had been no paleoseismic studies of the fault prior to 2005. Post-earthquake trenching showed a relatively short recurrence time of ~2 kyr for this fault.
CONCLUSION: paleoseismic studies AFTER the earthquake identified this fault as dangerous, but were not in time to be useful.

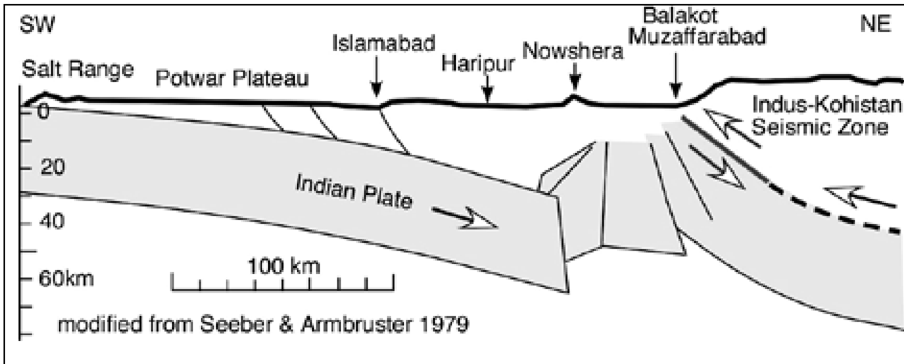

Figure 3. Schematic cross-section of the Muzaffarabad fault (right-center), source of the 2005 Kashmir earthquake. From http://cires.colorado.edu/~bilham/Kashmir%202005.htm.

2004 Sumatra-Andaman; 26-DEC-2004; 283,000 dead; a M 9.1 earthquake on the subduction zone between the Indian plate and the Burma plate (Sumatra subduction zone); The convergence rate across the subduction zone was well known from GPS measurements, so recurrence of M8 could be estimated even without paleoseismic studies. Zachariasen and others (2000) deduced a mean recurrence interval of 230 years (1370 AD, 1608 AD, 1833 AD) for the central segment of the subduction zone, two segments south of the segment that ruptured in 2004. However, the tsunami hazard of all segments was overlooked, and no paleo-tsunami evidence was known (but none had been looked for prior to 2004).

2003 Iran (Bam); 31,000 dead; a M 6.4 earthquake on a nearly-blind fault (strike-slip and thrust movement), difficult to detect or characterize without detailed surface mapping, or LIDAR DEM. The causative fault was first identified with InSAR, then with field observations. The fault trace was very vague and low-relief, and no paleoseismic studies had been performed prior to 2003.
CONCLUSION: because this fault had not been studied, local residents had no idea it posed a critical hazard to their city.

2001 India (Bhuj); 20,000 dead; a M 7.6 "blind" reverse fault in a Stable Continental Interior (Bodin and Horton, 2004). The source fault was inferred to be an ancient failed rift fault, like in the New Madrid Seismic Zone). Geologists knew big earthquakes occurred in the Rann of Kutch, but thought they all formed coseismic fault scarps like the Allah Bund, the 6 m-high scarp formed by the great 1819 earthquake. However, the 2001 earthquake formed very small scarps in friable sandy deposits on a sparsely-vegetated plain, so surface evidence would be destroyed in just a few years or decades. The causative fault had not been previously mapped.
CONCLUSION**:** as at Bam**,** the causative fault had not been identified (much less studied), and residents of Bhuj had no idea it posed a critical hazard to their city.

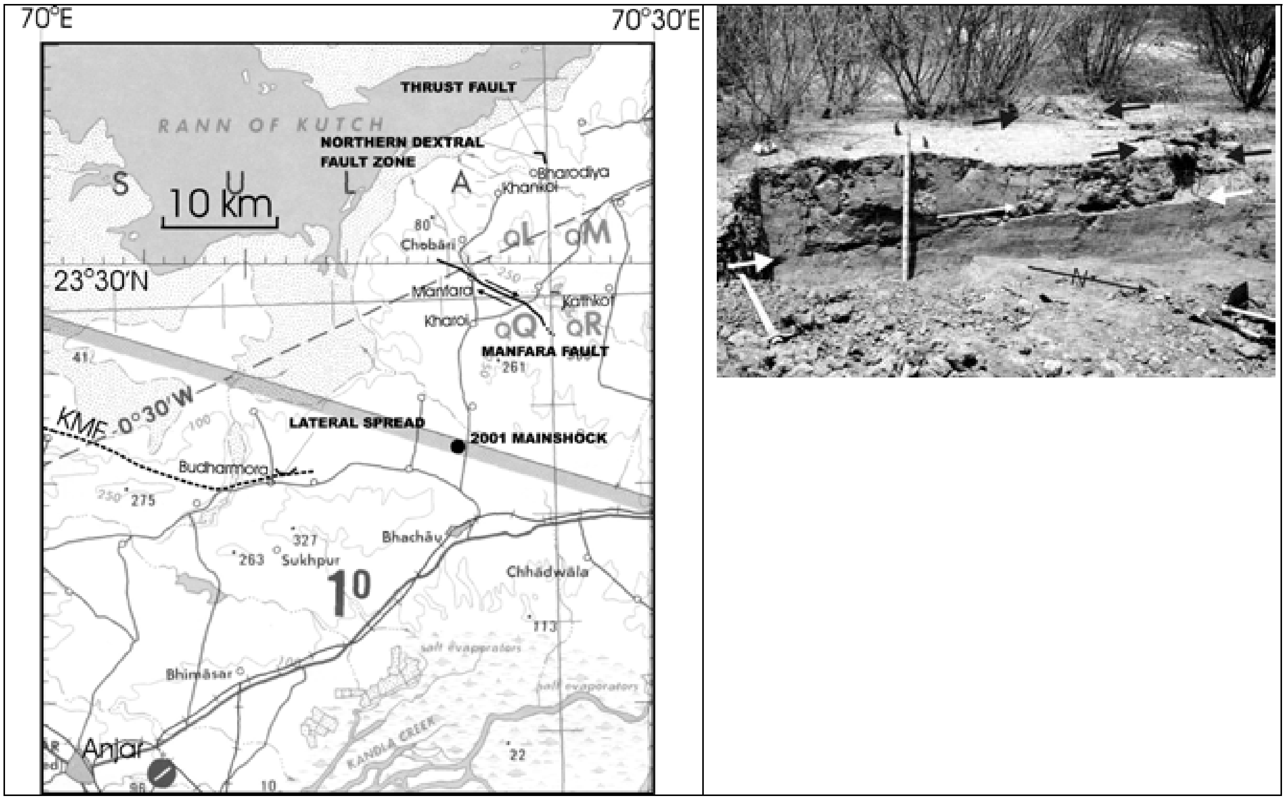

Figure 4. *Left*: Map of the 2001 mainshock, lateral spread, and Manfara fault, and northern dextral/thrust zone. *Right*: Photo of the northern thrust fault (white arrows) exposed in a cleaned-off gully wall. The thrust dipped 13º with 23 cm of net slip, and created a 15-20 cm-high moletrack (black arrows) several hundred meters long. From McCalpin and Thakkar, 2003.

SUMMARY OF THE SITUATION IN 2011

1-- in the first 40 years of Paleoseismology, we picked most of the “low-hanging fruit”, via studies of the long, obvious, high-slip-rate faults

2– what is left NOW are the poorly-preserved faults (Sichuan, Kashmir), the long-recurrence faults (>50-100 kyr), the offshore faults (Sumatra), & the blind faults (Bhuj, Bam) with their overlying folds

3-- COMMON FEATURES of the deadly earthquakes of 2000-2009

a- all reverse faults;

b– fault daylights at bases of steep ridges; OR blind faults, or offshore

c- if Quaternary fault scarps existed, they were poorly preserved, so hazard was underestimated

- Cultivation or natural slopewash erosion
- Low slip rate <1 mm/yr and long recurrence (several kyr)

4– as we learned in 2000-2009, these faults are too dangerous to overlook, especially:

a--reverse faults that are blind or have low slip rates, but characteristic earthquakes of M7-8

b--the M7 earthquakes may be more dangerous, because geologic evidence (scarps) will be small/ nonexistent, AND they are more frequent

WE HAVE BEEN STUDYING THE WRONG FAULTS

In the USA we have always classified faults as "active" depending on the age of their last characteristic earthquake (or surface rupture). This practice has led to a widespread but generally unstated assumption, that the most dangerous faults are those which have ruptured the most recently (that is, have the shortest Elapsed Times). This assumption does have an indirect basis in fact, because faults with high slip rates tend to have shorter recurrence times, thus the fast-slip-rate faults tend to (as a group) have shorter Elapsed Times at any given time than slow-slip-rate faults. And yet, 4 of the 6 devastating earthquakes cited above were NOT on fast-slip-rate faults! Instead, they were on slow-slip-rate faults that had reached the end of their seismic cycle.

What the above observation suggests, is that the hazard posed today by the faults in the USA depends on how far advanced they are in their seismic cycle, rather than being proportional to their slip rate, or inversely proportional to their Elapsed Time.

WHY THIS IS IMPORTANT

To anticipate a characteristic earthquake in the USA, we need to identify those that have either: (1) an elapsed time equal to or greater than their mean recurrence, or (2) an accumulated strain equal to or greater than their mean displacement per event. Traditionally, assessing a fault's status within its current seismic cycle has been an expensive and tedious exercise, culminating in a calculation of Conditional Probability of rupture in the next 50-100 years. Such forecasts have been made by the Working Groups on California Earthquake Probabilities since the late 1980s (1988, 1990, 1995, 2008), and by more informal groups elsewhere (e.g., the Wasatch fault; McCalpin and Nishenko, 1996). It has been felt that to support a Conditional Probability estimate, you must have a statistically robust estimate of mean recurrence, based on long paleoseismic records from trenches. For the normal faults in the western USA, this has required deep "megatrenches" such as on the Wasatch fault, as a supplement to the dozens of prior, smaller trenches. To achieve the first Conditional Probability estimate for ruptures of Wasatch fault segments, McCalpin and Nishenko (1996) had to synthesize the results of 15 years of work by USGS and its contractors, arising from 65 trenches costing millions of dollars. If we have to devote 15 years and millions of dollars to each fault to derive a traditional calculation of Conditional Probability, it will take us a century or more to identify which faults are about to rupture in the USA. But there is a faster way.

For any fault, the probability of rupture increases rapidly after the Elapsed Time (ET) has exceeded the Mean Recurrence Interval (RI). Simply comparing these two parameters for USA faults would tell us something about their status within their present seismic cycle. By ranking faults in a given State by their ET/RI ratio, we could provide State seismologists, seismic hazard analysts, and emergency planners with a way to prioritize which faults to devote resources to studying. That is what is happening right now on the Brigham City segment of the Wasatch fault, the Elapsed Time of which is nearly twice the Mean Recurrence Interval. It would be very helpful if we could "mine" existing data to identify any other "due" or "overdue" faults within the USA. Such data already exists, within the Quaternary Fault and Fold Database of the United States (http://earthquake.usgs.gov/hazards/qfaults/).

Therefore, a first step would be to "mine" the U.S. Quaternary Fault and Fold database for elapsed time, recurrence interval, and slip rate. From these parameters we can compute two indicators of position within the seismic cycle. The first is the ratio of ET/RI. Any faults with a ratio >1.0 are faults that should receive high priority for further study. Conversely, faults that have low ratios (say, <0.2) due to a short Elapsed Time, would not be high-priority faults to study. The ratio of ET/RI is already tabulated for all faults in Japan (Active Fault Database of Japan) and is called the "elapsed time rate" (http://unit.aist.go.jp/actfault-eq/english/index.html).

Second, some faults may not have enough data on mean recurrence to be statistically significant, especially if there have not been a lot of trench investigations on them. However, they may have more robust estimates of long-term slip rate from fault scarp heights on surfaces of various ages. If the age of the MRE on such a fault is known, then the Elapsed Time is also known, and the "accumulated slip" can be calculated by multiplying the Elapsed Time times the long-term slip rate. Accumulated slip (or accumulated strain) increases through the seismic cycle until a characteristic earthquake occurs, at which time it is released as coseismic displacement on the fault. Therefore, as the accumulated slip approaches the mean displacement per event on a fault, the probability of rupture increases. Faults within a given State can also be ranked by the ratio of accumulated slip:mean displacement per event. When ratios are >1.0, the accumulated slip exceeds the mean displacement per event, and probability of rupture is high.

WHY NOW IS THE TIME TO DO THIS

The USGS Quaternary Fault and Fold Database (herein the Database) has only been sparsely updated since its inception in the early 1990s, and is now badly in need of updating. USGS recognizes this and is embarking on a multi-year internal project, as manpower permits, to redigitize the fault traces and to update the Fault Summary Reports. USGS needs to update the database with all published data from paleoseismic studies performed after the original compilation. In addition, USGS needs to fix the positional errors in its Quaternary Fault GIS coverage, which are as large as 1000 m.

ACTION ITEMS TO SOLVE THE PROBLEM

Traditionally, assessing a fault's status within its current seismic cycle has been an expensive and tedious exercise, culminating in a rigorous calculation of Conditional Probability of rupture in the next 30-100 years. We obviously need a faster, cheaper method of assessing how far advanced faults are within their seismic cycle. Deriving the two ratios described above would be the first step in identifying faults with a high probability of rupture in the near future.

Action 1; Update the U.S. Quaternary Fault & Fold Database

The Database (http://earthquake.usgs.gov/hazards/qfault) was created between 1993 and about 2000 (http://earthquake.usgs.gov/hazards/qfault/aboutus.php). This Database is a one-stop-shopping location for consultants and academics working on seismic hazards. As the *About Us* Web page states, "*Our website presents—for the first time—a single source that summarizes important information on paleoseismic (ancient earthquake) parameters*." As a full-time consultant, I and most of my consultant colleagues "mine" this Database routinely as the first step in any seismic hazard study.

However, due to the large number of faults in the Database (1,694 excluding California; see Table 1) and the lack of assigned manpower at USGS, it has not been possible to keep it updated. In the 18 years since the earliest entries into the database, there have been many additional fault studies in the 12 States covered by the Database. Most of these new studies have NOT been incorporated into the on-line Database.

Table 1. Faults used as line sources in the 2008 National Seismic Hazard Map, listed by State, compared to the total number of Quaternary Faults in that State. From McCalpin, 2009a.

STATE	No. of Faults in National Seismic Hazard Map[1]	No. of Quaternary Faults In the USGS Q. Fault & Fold Database[2]	Percentage of Q. Faults Used in the National Seismic Hazard Map
Arizona	7	108	7%
Colorado	3	97	3% (the lowest)
Idaho	8	86	9%
Montana	15	87	17%
Nevada	119 (by far the highest)	622 (by far the highest)	19%
New Mexico	30	175	17%
Oklahoma	1	2	50%
Oregon	44	143	31%
Texas	12	28	43%
Utah	26	216	12%
Washington	17	51	33%
Wyoming	9	79	11%
	SUM=291	SUM=1694	AVERAGE=17%

[1] Petersen and others, 2008 (http://gldims.cr.usgs.gov/webapps/cfusion/hazfaults_search/hf_search_main.cfm
[2] http://gldims.cr.usgs.gov/webapps/cfusion/Sites/qfault/index.cfm

Two examples will suffice:

(1) In 2003 NEHRP funded GEO-HAZ Consulting and University of Texas at El Paso to re-trench the East Franklin Mountains fault (EFMF) at El Paso and apply luminescence dating to refine slip rate and recurrence. The EFMF had been included as a fault source in the National Seismic Hazard Map, with a slip rate of 0.1 mm/yr, which made it the dominant source of ground motion to El Paso at longer return periods. We discovered that the previous trenching had miscorrelated beds across the fault, and the true slip rate was 0.18 mm/yr, an increase of 80% over the old slip rate. The new slip rate was reported in the Final Technical Report to USGS-NEHRP in 2005 and incorporated into the 2008 revision of the National Seismic Hazard Map (Petersen et al., 2008). However, the on-line Database entry as of late 2010 for the EFMF does not contain any of this information; it is still the original compilation from 1995 (E.E. Collins and M.N. Machette).

(2) In 2001 USGS began detailed study of the Clan Alpine fault, central Nevada. The two lead scientists were, coincidentally, the creators and managers of the Database. Who could blame them, after being cooped up in an office for 7 years, for grabbing their Bruntons and bolting out to the field once the Database was finished? Their study resulted in a Web page at USGS (http://earthquake.usgs.gov/regional/imw/imw_clan_alpine/) dated September 2002 and a USGS SIM Map (Machette and others, 2005). However, the on-line Database entry for the Clan Alpine fault as of late 2010 was still the original one dated 2000 (by David J. Lidke). It does contain some new descriptive data in the "Paleoseismology Studies" section that was added at some time

after September 2001, but the age dates were not yet available so none of the other data sections were updated.

This general lack of updating of the Database is not acknowledged in the *About Us* Web page cited above. Thus, at present consultants using the Database may not realize the Database lacks recent fault data for their fault(s) of interest. This situation is not optimum if the consultants are relying on the Database to prepare reports for clients, which carry some legal liability.

Action 2; Compile data on Indicator 1: Elapsed Time *versus* Mean Recurrence

The simplest way to assess a fault's position within its current seismic cycle is to compare the Elapsed Time since the MRE, to the fault's Mean Recurrence Interval. The Elapsed Time has been recorded for almost every fault that has been trenched, or for which an age estimate has been made from morphologic grounds (e.g., a fault scarp diffusion age). The Mean Recurrence Interval is a bit less common, because it requires more data. For faults that have been trenched, it requires dating a minimum of two successive paleoearthquakes; more are better. For faults that have not been trenched, a long-term Mean Recurrence Interval can be calculated from morphologic data, by dividing the age of a faulted deposit or geomorphic surface by the inferred number of surface faulting events. The number of faulting events is typically estimated from multiple-event fault scarp heights, the heights of which are often simple multiples of single-event fault scarp heights.

Action 3; Compile data on Indicator 2: Accumulated Strain *versus* Mean Slip-Per-Event

The accumulated strain on a Quaternary fault can be estimated by multiplying the fault's long-term Slip Rate (mm/yr) times the Elapsed Time (yr). Both of these parameters are quoted for many faults in the Database. Less commonly available is the mean displacement-per-event for paleoearthquakes on a fault, because that requires one or more trenches. However, there are still many Quaternary faults in the USA that have been trenched.

A renewal model for characteristic earthquakes assumes that a fault will rupture when its accumulated strain reaches the level needed to overcome fault friction. The result is a characteristic earthquake, with characteristic magnitude and characteristic slip. So, if we knew the value of characteristic slip for a given fault, we can compare it with the accumulated strain on that fault since its MRE. Any faults that have accumulated more strain (say, 1.8 m) compared to a mean displacement-per-event (say, 1.0 m), would be interpreted as having a higher probability for rupture, and would be the logical faults on which to concentrate future research.

Action 4; Rank Faults by Indicators 1 and 2

Once we have computed Indicators 1 and 2 for all possible Quaternary faults in the USA, we can simply rank them in State-by-State lists. In both cases the Indicators are dimensionless, with a value range from 0 to perhaps as much as 2.0, with higher values indicating that a fault has advanced farther in its current seismic cycle. In particular, any values >1.0 indicate that the elapsed time or accumulated strain on a fault has already exceed the mean values for that fault. These faults should be considered high priority targets for additional study, assuming that there is sufficient population or infrastructure in their vicinity to constitute significant risk. Additional study should be aimed at collecting the detailed but expensive trenching data needed to properly calculate robust Conditional Probability estimate of rupture in the near future.

APPLICATION TO LAS VEGAS

The Las Vegas metropolitan area contains numerous Quaternary faults (Figures 4, 5, 6). The longest and best-known are the Frenchman Mountain fault, which bounds Las Vegas Valley on the east side, and the Eglington fault in the northwest part of the valley. According to the US Quaternary Fault and Fold Database, these faults have moved in the past 130,000 years. In addition there are 25 other mapped faults in the central, urbanized part of the valley. USGS calls these faults the Las Vegas Valley Class B faults, indicating that they are confident the faults are tectonic and seismogenic. That family of faults has been little studied; USGS cites their latest movements as younger than 1.6 million years old.

The Las Vegas Valley faults, as defined by USGS, include about 25 individual fault strands with a cumulative length of roughly 160 km (Figure 4) These strands have been informally grouped and named by local geologists; from west to east, the West Charleston, Decatur, Valley View, Cashman, and Whitney Mesa faults; see Figure 5). For the Las Vegas Valley faults (Appendix 3), most information comes from unpublished consulting reports in which trenches failed to even find faults. The sole published exception is by dePolo and others (2006) on the northern part of the Valley View fault. The elapsed time is cited by dePolo and others (2006) as ca. 14.5 ka and recurrence interval is unknown; thus ET/RI cannot be computed. Accumulated strain since the MRE is $\leq$0.2 m/ka (cf. Appendix 3) since 14.5 ka, or ca. 2.9 m. dePolo and others (2006) measured displacements per event of 2-3 m on the northern part of the Valley View fault. Therefore, the accumulated strain of 2.9 m is larger than most of the range of displacements per event, suggesting a high probability of future rupture.

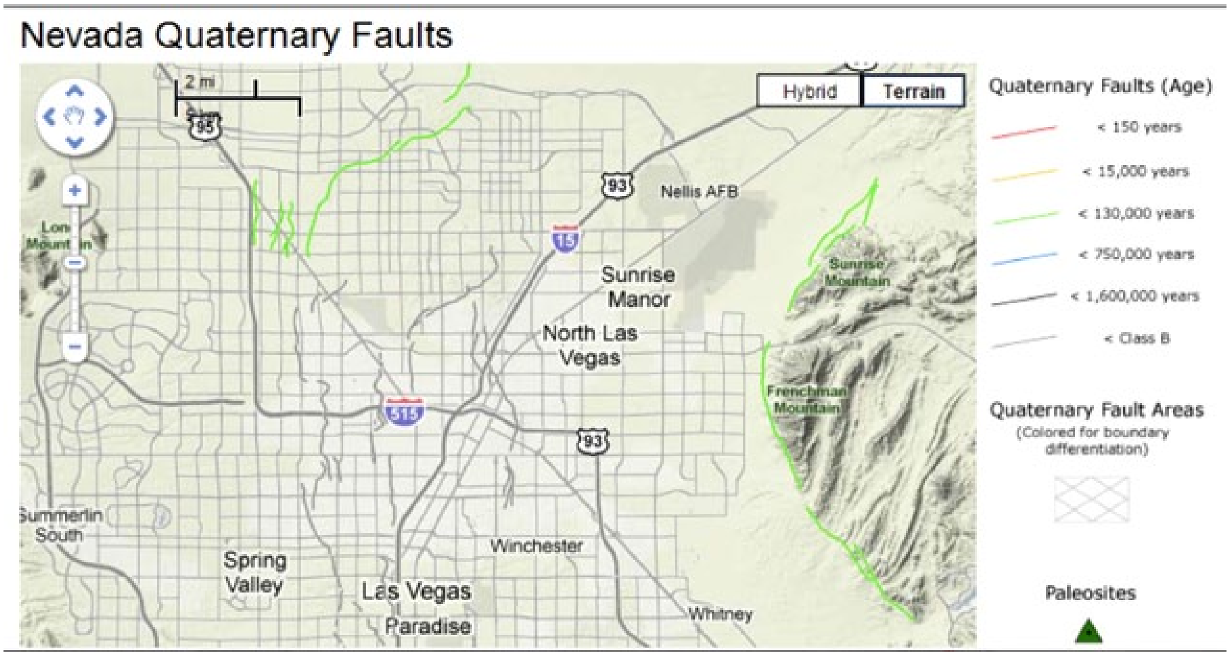

Figure 4. Quaternary faults in Las Vegas, from the US Quaternary Fault and Fold Database (Petersen, 2008). Green fault at upper left is the Eglington fault; at lower right is the Frenchman Mountain fault. Both have moved in the past 130,000 years. Gray faults are named the Las Vegas Class B faults by USGS, with movement younger than 1.6 million years

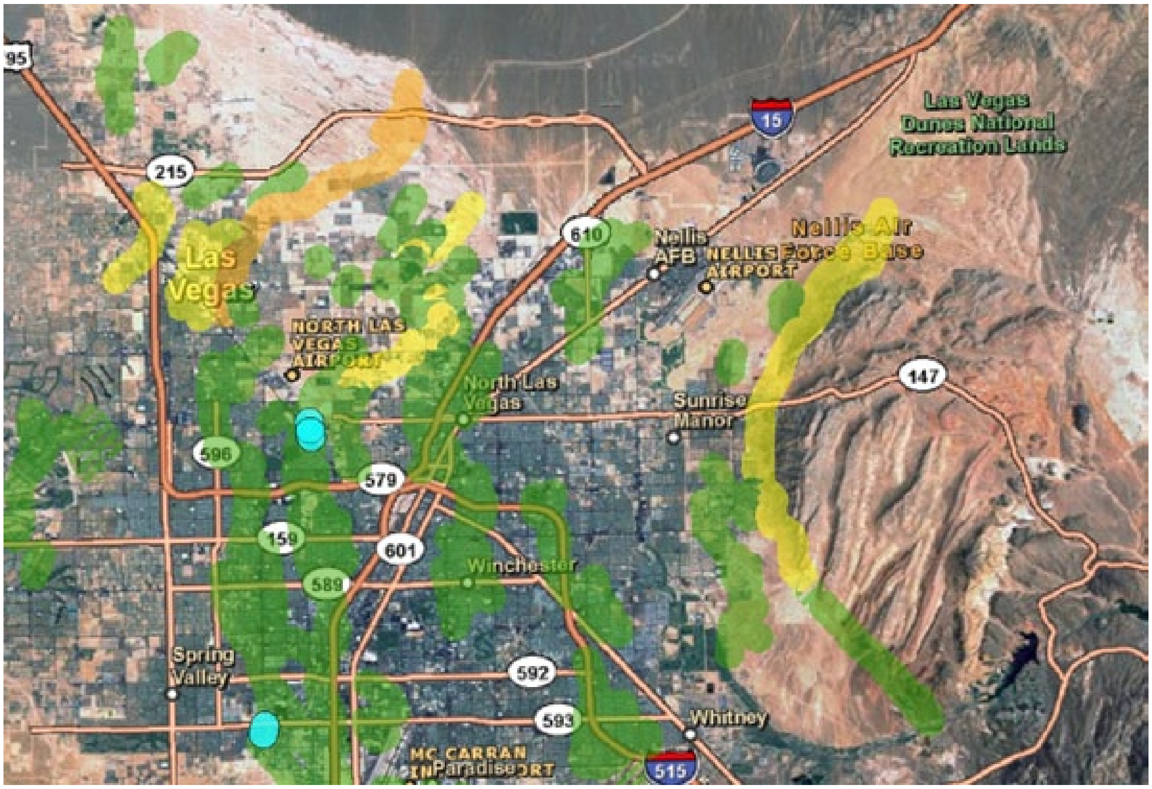

Figure 5. Quaternary faults from the Nevada Bureau of Mines and Geology on-line fault database (2009). Orange faults (Eglington) have moved in the past 15,000 years; yellow faults in the past 130,000 years; green faults in the past 750,000 years.

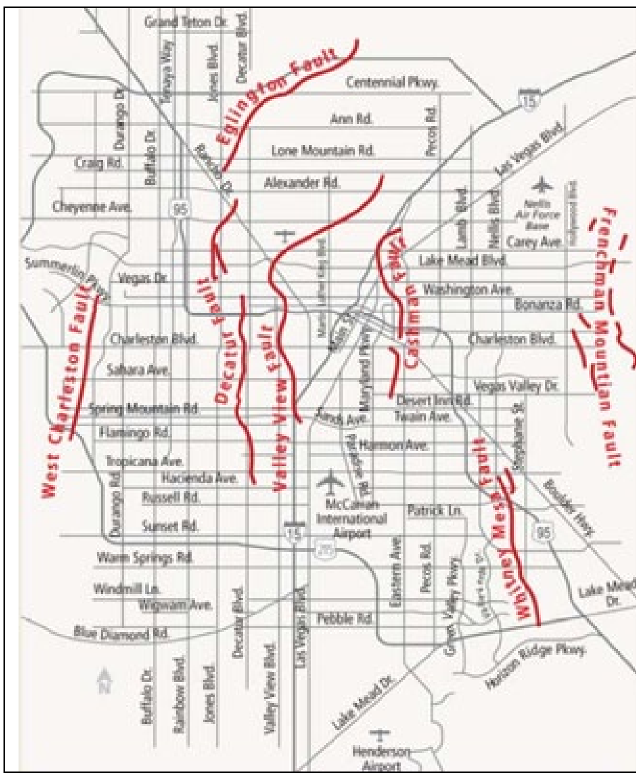

Figure 6. Map of named faults in the Las Vegas Valley. Source: *Las Vegas Review-Journal*, 14-MAY-2008.

For the Frenchman Mountain fault (Appendix 1), the elapsed time is poorly constrained (10 to 130 ky) and recurrence interval is unknown; thus ET/RI cannot be computed. Accumulated strain since the MRE is 0.015 m/ka since 10 to 130 ka, or 0.15 m to 1.95 m. Unfortunately, the Database has no information about displacement per event, so we cannot compare accumulated strain to it.

For the Eglington fault (Appendix 2), the elapsed time is cited by Taylor (unpub.) as 2245 yBP and recurrence interval is unknown; thus ET/RI cannot be computed. Accumulated strain since the MRE is 0.2 to 1.0 m/ka since 2.245 ka, or 0.45 to 2.2 m. Unfortunately, the Database has no information about displacement per event, so we cannot compare accumulated strain to it. The problem of earthquakes occurring on faults that were not considered dangerous and thus were not studied, was mentioned by State Geologist Jonathan Price, in the Introduction.

CONCLUSIONS

The USA is not immune to the type of deadly earthquakes that occurred worldwide in 2000-2010; M 6.5-7.5 earthquakes on low-slip-rate faults. The present methods of seismic hazard assessment (PSHA) used in the USA assume that the probability of the next characteristic earthquake on a fault in a given time period (e.g., 10 years to 100 years) is independent of where that period falls within the fault's seismic cycle. This is equivalent to saying that the fault has no memory, and that the fault does not obey the elastic rebound theory, but generates characteristic earthquakes randomly in time (this is the "memoryless", or Poisson, assumption). Using that approach, all of the killer earthquakes that occurred in 2000-2010 had a very low probability of occurring. Yet they occurred.

The truth is, that as strain slowly rebuilds on a fault after a characteristic earthquake, the probability of the next characteristic earthquake increases through time. Therefore, it is critical to know the position of a Quaternary fault within its current seismic cycle. Past paleoseismic investigations have not focused on this aspect, but have been more concerned about dating the latest characteristic earthquake on the fault, because fault regulations are tied to the age of latest fault movement. However, for determining where a fault currently is within its seismic cycle, we need to know: (1) the ratio of the elapsed time to the mean recurrence interval, or (2) the ratio of accumulated strain to the mean displacement per event. Paleoseismic investigations should now be focused on those four parameters.

In the USA, databases containing Quaternary fault parameters were compiled without much regard to the seismic cycle, and the descriptions of many faults do not contain usable parameter data needed to assess a fault's position within its current seismic cycle. This can be seen for the case of Quaternary faults in the Las Vegas Valley. As long as we continue this approach to paleoseismology, we will continue to devote our limited resources to studying the wrong faults, and earthquakes will continue to surprise us, occurring on "unexpected", low-slip rate faults and killing unprepared people.

REFERENCES

Bilham, R., Gaur, V.K., and Molnar, P., 2001, Himalayan Seismic Hazard: *Science*, v. 293, p. 1442-1444.

Bodin, P. and Horton, S., 2004, Source parameters and tectonic implications of aftershocks of the Mw 7.6 Bhuj earthquake of 26 January 2001: Bulletin of the Seismological Society of America, v. 94; no. 3; p. 818-827; DOI: 10.1785/0120030176

CRED, 2011, Emergency events database: Collaborating Centre for Research on the Epidemiology of Disasters (CRED), World Health Organization and the Belgian Government: http://www.emdat.be/database.

DeMets, C.; Wiggins-Grandison W. (2007). Deformation of Jamaica and motion of the Gonâve microplate from GPS and seismic data: Geophysical Journal International**,** v. 168, p. 362–378.

Densmore A.L., M.A. Ellis, Y. Li, R. Zhou, G.S. Hancock, and N. Richardson, 2007, Active tectonics of the Beichuan and Pengguan faults at the eastern margin of the Tibetan Plateau: Tectonics, v. 26, TC4005, doi:10.1029/2006TC001987 (2007).

dePolo, C.M., Bell, J.W., Borron, S., Slemmons, D.B. and Werle, J.L., 2006, Late Quaternary fault movement along the Las Vegas Valley fault system, Clark County, Nevada: Environmental and Engineering Geoscience, v. XII, no. 2., p. 181-193.

Hayes, G.P., Briggs, R.W., Sladen, A., Fielding, E.J., Prentice, C., Hudnut, K., Mann, P., Taylor, F.W., Crone, A.J., Gold, R., Ito, T. and Simons, M., 2010, Complex rupture during the 10 January 2010 Haiti earthquake: Nature Geoscience, v. 3, p. 800-805.

Machette, M.N., Haller, K.M., Ruleman, C.A., Mahan, S. and Okumura, K., 2005, Evidence for late Quaternary movement on the Clan Alpine fault, west-central Nevada; Trench logs, location maps, and sample and soil descripotions: U.S. Geological Survey Scientific Investigations map 2189.

Mann, Paul, Calais, Eric, Demets, Chuck, Prentice, Carol S, and Wiggins-Grandison, Margaret (March 2008). "Entiquillo-Plantain Garden Strike-Slip Fault Zone: A Major Seismic Hazard Affecting Dominican Republic, Haiti and Jamaica". *18th Caribbean Geological Conference.*

McCalpin, J.P. (ed.), 2009, Paleoseismology, 2nd Edition: Academic Press (an imprint of Elsevier, Amsterdam), 613 p.

McCalpin, J.P. and Niskenko, S.P., 1996, Holocene paleoseismicity, temporal clustering, and probabilities of future large (M>7) earthquakes on the Wasatch fault zone, Utah: Journal of Geophysical Research, v. 101(B3), p. 6233-6253.

McCalpin, J.P. and Thakkar, M.G., 2003, 2001 Bhuj-Kachchh earthquake; surface faulting and its relation with neotectonics and regional structures, Gujarat, western India, in Pantosti. D., Berryman, K., Yeats, R. and Kinugasa, Y. (eds.), Ten Years of Paleoseismology in the ILP, Progress and Prospects: Annals of Geophysics, v. 46, no. 5, p. 937-956.

Petersen, M.D., Frankel, A.D., Harmsen, S.C., Mueller, C.S., Haller, K.M., Wheeler, R.L., Wesson, R.L., Zeng, Y., Boyd, O.S., Perkins, D.M., Luco, N., Field, E.H., Wills, C.J. and Rukstales, K.S., 2008, Documentation for the 2008 update of the United States National Seismic Hazard Maps: U.S. Geological Survey Open-File Report 2008-1128, 61 p.

Prentice, C.S., Mann, P., Crone, A.J., Gold, R.D., Hudnut,, K.W., Briggs, R.W., R. D. Koehler, R.D., and Jean, P., 2010, Seismic hazard of the Enriquillo–Plantain Garden fault in Haiti inferred from palaeoseismology: Nature Geoscience, v. 3. p. 789-793.

Seeber, L. and Armbruster, J., 1979, Seismicity of the Hazara arc in northern Pakistan; Decollement versus basement faulting, in Farah, A. and De Jong, K.A. (eds.), Geodynamics of Pakistan: Pakistan Geological Survey, p. 131-142.

Utsu, T., 2002, A list of deadly earthquakes in the world: 1500–2000, *in* Lee, W.K., Kanamori, H., Jennings, P.C. and Kisslinger, C. (eds.), International Handbook of Earthquake Engineering and Seismology: Academic Press, Elsevier Publishers, Amsterdam and Boston, p. 691-717.

Wells, R.E. (ed.), 2004, The Loma Prieta, California, earthquake of October 17, 1989; Geologic setting and crustal structure: U.S. Geological Survey Professional Paper 1550-E, 204 p.

Working Group on California Earthquake Probabilities (1988). Probabilities of large earthquakes occurring in California on the San Andreas fault. U.S. Geol. Surv. Open File Rep. 88–398, p. 1–62.

Working Group on California Earthquake Probabilities (1990). Probabilities of large earthquakes in the San Francisco Bay region, California. U.S. Geol. Surv. Circ. 1053, p. 1–51.

Working Group on California Earthquake Probabilities (1995). Seismic hazards in southern California-Probable earthquakes, 1994–2024. Bull. Seis. Soc. Amer., v. 85, p. 379–525.

Working Group on California Earthquake Probabilities (2008). The uniform California earthquake rupture forecast, version 2 (UCERF 2). U.S. Geol. Surv. Open File Rep. 2007–1437: Also Calif. Geol. Surv. Spec. Rep. 203, 104 pp.

Zachariasen, J., K. Sieh, F. Taylor, and W. Hantoro, 2000, Modern vertical deformation above the Sumatran subduction zone: Paleogeodetic insights from coral microatolls: Bull. Seis. Soc. Amer., v. 90, p. 897-913.

APPENDICES (from the on-line Quaternary Fault and Fold Database of the United States, accessed Feb. 21, 2011).

Appendix 1.Part of the Complete Report for the Frenchman Mountain fault, from the US Quaternary Fault and Fold Database. Elapsed time, recurrence interval, and slip rate.

Most recent prehistoric deformation	Late Quaternary (<130 ka) *Comments:* The fault cuts deposits estimated to be late Pleistocene (Anderson and O'Connell, 1993 #1440), and the last displacement event produced a scarp about 2 m high. Late to mid Holocene (<5 ka) deposits are probably not faulted, and, on the basis of the strongly eroded nature of the scarps, the youngest displacement event is inferred by Anderson and O'Connell (1993 #1440) to be much older, probably late Pleistocene (10-130 ka), which is consistent with the late Pleistocene age estimated by Dohrenwend and others (1991 #288) on the basis of photogeologic mapping at scale of 1:250,000.
Recurrence interval	*Comments:* According to Anderson and O'Connell (1993 #1440), the Frenchman Mountain fault has had multiple Quaternary displacements, but neither the recurrence interval nor the time of last displacement event is

	known.
Slip-rate category	Less than 0.2 mm/yr *Comments:* According to Anderson and O'Connell (1993 #1440), the Frenchman Mountain fault has had multiple Quaternary displacements summing to several meters of offset, but age control is insufficient to determine the slip rate. Slemmons (1999 #4708) reported that the slip rate ranges from 0.03-0.1 mm/yr, but the basis for that determination is not reported. dePolo (1998 #2845) calculated a vertical slip rate of 0.015 mm/yr for the fault based on 7.5 m of offset of a deposit estimated to be 500 ka. The late Quaternary characteristics of this fault (overall geomorphic expression, continuity of scarps, age of faulted deposits, etc.) support a low slip rate. Accordingly, the less than 0.2 mm/yr slip-rate category has been assigned to this fault.
Date and Compiler(s)	1999 R. Ernest Anderson, U.S. Geological Survey

Appendix 2. Part f the Complete Report for the Eglington fault, from the US Quaternary Fault and Fold Database. Elapsed time, recurrence interval, and slip rate.

Most recent prehistoric deformation	Late Quaternary (<130 ka) *Comments:* If the Eglington scarp is associated with paleoearthquakes, the last displacement event probably occurred 14-30 ka (Bell and dePolo, 1998 #4710). For the other scarps [1120], the last faulting event is probably much older, Quaternary to perhaps Pliocene along some scarps. Geodetic monitoring of subsidence caused by overdrafting of groundwater in Las Vegas Valley is interpreted (Bell and dePolo, 1998 #4710) as having reactivated faults. **Wanda Taylor (UNLV) said the Eglington Fault, on the valley's north side, produced an earthquake 2,245 years ago, based on mesquite charcoal that was found below the surface (Las Vegas Review-Journal, 14-MAY-2008).**
Recurrence interval	*Comments:* According to Slemmons (1998 #4708) recurrence intervals are unconstrained.
Slip-rate category	Less than 0.2 mm/yr *Comments:* Slip rates of 1-1.5 mm/yr are estimated for the Eglington scarp (dePolo and Ramell, 1998 #4707; Bell and dePolo, 1998 #4710), but even the proponents of a predominantly tectonic origin of the scarps, question the tectonic significance of such high rates. dePolo (1998 #2845) did not include preferred rates in his tabulation, but dePolo and Ramelli (1998 #4707) suggested a rate of about 1.0 mm/yr. Other than evidence for fairly recent faulting (14-30 ka, Bell and dePolo, 1998 #4710), the late Quaternary characteristics of this fault (overall geomorphic expression, continuity of scarps, age of faulted deposits, etc.) support a low slip rate. Accordingly, the less than 0.2 mm/yr slip-rate category has been assigned to this fault.
Date and Compiler(s)	1999 R. Ernest Anderson, U.S. Geological Survey

Appendix 3. Part of the Complete Report on the Las Vegas Valley faults, Class B, from the US Quaternary Fault and Fold Database. Elapsed time, recurrence interval, and slip rate.

Most recent prehistoric deformation	Late Quaternary (<130 ka) *Comments:* If the Eglington scarp is associated with paleoearthquakes, the last displacement event probably occurred 14-30 ka (Bell and dePolo, 1998 #4710). For all other scarps, the last faulting event is probably much older, perhaps

	Pliocene along some scarps. Geodetic monitoring of subsidence caused by overdrafting of groundwater in Las Vegas Valley is interpreted (Bell and dePolo, 1998 #4710) as having reactivated faults. **MRE slightly after 14.5 ka (dePolo et al., 2006).**
Recurrence interval	*Comments:* According to Slemmons (1998 #4708) recurrence intervals are unconstrained, but for the Eglington scarp [1733], a few thousand years is possible. For other scarps it would probably be much longer. DePolo and Ramelli (1998 #4707) suggested that the recurrence intervals of the Las Vegas Valley faults are probably measured in tens of thousands to hundreds of thousands of years.
Slip-rate category	Less than 0.2 mm/yr *Comments:* There are no data from which to estimate of slip rate. The late Quaternary characteristics of this fault (overall geomorphic expression, continuity of scarps, age of faulted deposits, etc.) support a low slip rate. Accordingly, the less than 0.2 mm/yr slip-rate category has been assigned to this fault.
Date and Compiler(s)	1999 R. Ernest Anderson, U.S. Geological Survey