# QUATERNARY FAULTS AND FOLDS IN THE UNITED STATES

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**Summary**
Our compilation of Quaternary faults and folds in the United States is part of a larger International Lithosphere Program Task Group II-2 project to compile a World Map of Major Active Faults. The U.S. compilation supplies robust data for regional comparisons of rates and patterns of active deformation. We focus mainly on structures that have produced documented surface deformation, such as fault scarps or folds, however subsurface faults are included based on their association with historic or prehistoric liquefaction features, such as sand blows. Although incomplete, this Internet-based GIS and relational computer database is an archive for paleoseismic data. Comparisons between major faults in transpressional, compressional, extensional, and intraplate regimes are showing important differences in styles of deformation, slip rates, recurrence intervals, and patterns of episodic behavior. This paper touches on some important aspects of and preliminary results from the project.

**Introduction**
As part of the International Lithosphere Program's Task Group II-2 "World Map of Major Active Faults," scientists from the U.S. Geological Survey, State Geological Surveys, universities, and private companies have created a Internet-based computer database and digital map of Quaternary faults and folds in the U.S. Although our compilation is only about 75 percent complete, it reveals some important differences between regional fault patterns, rates and styles of deformation across the country. (The compilation for Alaska has just started, thus faults in that region are not discussed specifically).

For the purposes of this discussion, the U.S. is categorized into three broad tectonic regimes: transpressional/compressional, extensional, and intraplate. These boundaries between these regimes are not sharply defined, but the divisions help compare and contrast regional rates and styles of deformation. In the following discussion, I highlight some characteristics of faults in each of the tectonic regimes.

Yeats and others (1997) listed 61 ground-rupturing earthquakes (GRE) that have ruptured historically in the conterminous (mainland) U.S.: this list provides a convenient perspective for reviewing the prehistoric record. The earliest GRE recorded was the 1812 "San Juan Capristrano" event on the San Andreas fault; the last shown are two earthquakes near Ridgecrest, California (however, the 1999 Hector Mine earthquake is the most recent). The average repeat time for a GRE in the U.S. is about 3 yrs. Yeats and others (1997) omitted large and devastating events that produced deformation, but had no demonstrable surface ruptures: these include the 1811-12 New Madrid earthquakes; the 1886 Charleston earthquake; many in California (such as 1934 Long Beach, 1979 San Fernando, 1982 Whittier Narrows, 1992 Petrolia, and 1994 Northridge), and a few in Washington (1870 and 1949).

The study of prehistoric surface or ground-rupturing earthquakes (hereafter abbreviated GRE) are of interest because they leave a geologic record and thus allow us to assess seismicity prior to our short historic record. This technique, which is known as paleoseismology, can extend the modern record of seismicity well back into the Quaternary. The majority of GRE have occurred in the Western U.S., primarily in California (44 recorded from 1812 to 1999) and Nevada (9 recorded since 1869). However, other notable GRE outside of western Nevada and California include the 1959 Hebgen (Montana) and 1983 Borah Peak (Idaho). The 1811-12 New Madrid (Missouri) sequence (3 events) and the 1886 Charleston (South Carolina) earthquakes caused massive sand blows as a result of strong-ground motion, and although no *bona fide* surface ruptures are known, they are discussed herein because of their large magnitude and occurrence in a region generally considered to be tectonically stable.

**West Coast transpressional/compressional tectonics**
The most active tectonic regions of the continental U.S. is the transpressional/compressional regime along the west coast and Alaska, where oblique motion between the North American, Pacific, and Juan de Fuca plates is accommodated along major strike-slip and subduction faults as well as associated thrust and fold belts. Slip rates (SR) on individual strike-slip structures range from several mm/yr to about 30 mm/yr, whereas recurrence intervals (RI) for M>6.5 GRE on faults are measured in centuries to millennia (Table 1). Because of the pronounced activity of these faults (high SR and low RI), patterns of historical seismicity image most of the important structures in these regimes. As a result, probabilistic seismic-hazard maps show a strong correlation to both active faults and historic seismicity. Nevertheless, a few major faults, such as the currently aseismic Garlock fault and Cascadia subduction zone, may not be factored into the assessment process if slip rate or recurrence data are not available. In addition, recent earthquakes on lesser known and less active structures, such as blind thrusts and minor strike-slip faults (which are often overlooked in assessments) have proven to be important contributors to seismic hazards. Since 1979, almost all of the large damaging earthquakes in Southern California have occurred on poorly known structures, and few of the more well known "active faults" contributed large damaging earthquakes. For example the most recent GRE (Mw 7.1 Hector Mine, Oct. 16, 1999) followed several pre-existing faults and broke new ground between them. The total rup-

ture length for the newest U.S. GRE is about 41 km, breaking in a NNW direction across the NW structural grain of the region. This pattern of rupturing is similar to that of the 1992 Landers GRE, some 30 km to the southwest.

*Table 1. Typical rates and styles of fault deformation in the U.S.*
[Abbreviations: SR, slip rate in ; RI, recurrence interval; k.y. thousands of yrs; ND, not determined]

| **Tectonic regime** | **SR** mm/yr | **RI** k.y. | **Style of deformation** |
|---|---|---|---|
| *Transpression* | | | Strike-slip faults, blind thrusts, folds |
| Common | 1-2 | 1-2 | |
| Extreme | 25 | 0.1-0.2 | |
| *Compression* | | | Subduction zone margin with folds, thrusts, and strike-slip faults |
| Average | 40 | 0.5 | |
| Extreme | N.D. | 0.3-1.7 | |
| *Extension* | | | Normal faults, minor folds & strike-slip faults |
| Common | <0.2 | 10-50 | |
| Extreme | 2.0 | 2 | |
| *Intraplate* | | | Blind thrusts(?), minor normal & strike-slip faults |
| Common | <0.005 | 50-100 | |
| Extreme | ND | 0.3-1.0 | |

**Examples of transpressional and compressional faults**

There are 44 documented historic GREs in California, but none along the West Coast in Oregon or Washington where deformation is driven by plate subduction. Based on geologic research in North America and historic records in Japan (Rogers and others, 1996), the largest earthquake on the Cascadia subduction zone occurred on Jan 26, 1700, prior to European setlement in the Pacific Northwest.

Major earthquakes along the Cascadia subduction zone pose the most significant seismic risk to the Pacific Northwest, both in the U.S. and Canada. Because the subduction zone is everywhere offshore, paleoseismic studies of its history have focused on the geologic effects caused by strong ground motion (mainly sand blows and liquefaction features), tsunamis, and subsidence/uplift (see Atwater, 1996). Clague's (1997) paper on evidence of large Cascadian earthquakes is a valuable summary of this important region. In terms of prehistoric earthquakes, Atwater and Hemphill-Haley (1997) have evidence for a great (M 8+) earthquake about once every 500 years in the Pacific Northwest, although the recurrence intervals vary from as little as 300 yrs to as much as 700-1,300 yrs over the past 3,500 years. The Jan. 26, 1700, Cascadia earthquake caused local subsidence and drowning of forests along estuaries of the Pacific Coast of Washington and Oregon; stumps from these forests are still preserved at a number of localities (see Atwater, 1996, fig. 14). The tsunami from the earthquake is recorded in historic documents in Japan. Most of the 40 mm/yr plate convergence is accomodated by subduction, but folding, thrusting and strike-slip faulting occurs as far inland as Seattle, Washington.

In contrast, the San Andreas and its associated strike-slip "sister faults" have been historically active. In California, "San Andreas type" faults (north-trending strike-slip with short RI and high SR) account for 9 of 14 earthquakes at M 6.7 or larger, or about 2/3rd of the cases. The last two truly damaging San Andreas type GRE were the 1906 San Francisco and the 1989 Loma Prieta. However, 30 of the 44 GRE of M<6.7 are on non-San Andreas type faults and although their rupture dimensions (length and offset) are proportionately smaller, they have caused the majority of earthquake damage in California. This realization has forced scientists and planners to acknowledge the potential hazard from smaller (M 6-7) GREs that occur on the lesser known faults and blind thrust faults, especially in the Los Angeles metro area.

Young faulting in the San Francisco area of California is characterized by 4 or 5 major subparallel strike-slip faults that accommodate most of the lateral motion between the Pacific and North American plates. Of these, the San Andreas is the major player with an estimated 14-24 mm/yr of lateral motion near San Francisco. However, the San Gregorio (3-7 mm/yr), Hayward (9 mm/yr), and Calaveras (6-15 mm/yr) faults are clearly major contributors in terms of accomodating plate motion. Recent and ongoing investigations of paleoseismicity in this area (lead by D.P. Schwartz as part of a USGS/PG&E project) coupled with an evolving catalog of GPS vector-motion data, have enabled the scientific community to fine-tune their 30-yr probability estimates for GRE in the San Francisco Bay area (Michael and others, 1999). This research is at the cutting edge of paleosesimology, and demonstrates the practical application of integrated multidisciplinary studies of active faults.

Movement on blind thrusts in the Los Angeles basin and Transverse Range to the north accommodate north-south compression: because of their local importance, slip rates and recurrence intervals for these faults are becoming well established through paleoseismic and GPS studies. Most of the topographic relief in the basin and adjacent ranges to the north results from upthrusting or folding (*i.e.*, Ventura anticline), whereas to the south of the Los Angeles basin, most of the deformation is accomodated by a series of subparallel strike-slip faults (San Andreas: 20-35 mm/yr; San Jacinto: 7-17 mm/yr; Elsinore: 4 mm/yr; and Englewood-Newport-Rose Canyon: 1-2 mm/yr).

The Mohave desert region (southeastern California) had received little paleoseismic attention prior to the 1992 Mw 7.4 Landers GRE, which was the largest earthquake in the continental U.S. since 1959 (Hebgen Lake, Montana). Subsequent trenching studies have shown that the rupture jumped between a series of subparallel NW-striking faults, resulting in a concave to the west, NNW-striking rupture path. Many of the reactivated faults are characterized by Holocene faulting, but their slip rates (0.5 mm/yr) are quite a bit slower and RIs (7-9 k.y.) much greater than the "San Andreas type" faults to the west.

The most recent "unexpected fault rupture" in the U.S. occurred on Oct. 16, 1999, when the Mw 7.1 Hector Mine earthquake struck a relatively quite region of the Mojave, northeast of the Landers rupture. This rupture followed a previously mapped section of the Bullion fault (Holocene) and unmapped Lavic Lake fault (pre-Holocene). The maximum right-lateral offset is 5.2 m (see preliminary report at http://www-socal.wr.usgs.gov/hector/). This rupture is strikingly similar to the Landers, and may be characteristic of faults within the Eastern California Shear Zone. The slip rate on the Lavic Lake fault is apparently <1 mm/yr and, thus, it should produce a GRE only infrequently. As stated in the above report "This event is a reminder that in areas with low slip-rate faults, it is erroneous to consider such faults as inactive solely because they have not produced an earthquake during Holocene time."

In southeastern California and along its boundary with Nevada, there are a series of primarily strike-slip faults that trend N to NW. These include faults of the Walker Lane (western Nevada) and Death Valley and Panamint valleys (southeastern California). Although these areas are within the classic Basin and Range province, they have high rates of right-lateral slip, which is uncharacteristic of the province. For example, the Furnace Creek-Death Valley fault system, which is the major seismic threat in this region, has an estimate slip rates of 4-10 mm/yr and recurrence intervals measured in hundreds of years (*i.e.*, a San Andreas type fault).

**Intermountain West extensional tectonics**

The second most tectonically active region in the U.S. is the extensional Intermountain West (IMW, longitude between east sides of the Sierra Nevadas and the Rocky Mountains), which includes the relatively active Basin and Range (B&R) province (9 of 61 GRE) and Rio Grande rift (RGR) (1 GRE in northern Mexico). Most IMW faults have normal slip at rates of <0.2 mm/yr, whereas the most active are moving at 1-2 mm/yr. Their RIs range from 2 to 50 k.y. (Table 1). Although most IMW faults have long histories of infrequent but repeated movement, the characteristic extensional topography of the B&R province is largely a product of earlier (Pliocene or Miocene) extension. If one assumes that a 0.2 mm/yr slip rate is a reasonable upper bound for most of these faults (Table 1), then only about 300 m of offset (and less relief owing to deposition) was generated during the Quaternary (1.6 Ma). In the RGR of New Mexico, an episode of accelerated extension formed most of the present topography by early(?) Pliocene time (Machette, 1996).

Except for the B&R and RGR, most of the broader IMW is relatively stable. Quaternary faults are sparse throughout the region, and although recurrent faulting has occurred, significant fault topography has not developed owing to low rates of displacement. Most of the Colorado Plateaus and Wyoming Basin provinces fit into this category. These faults have SRs that are typically <0.05 mm/yr and RIs of >20-100 k.y.

**Examples of extensional faults**

The most active portion of the IMW is the Central Nevada Seismic Belt (CNSB), which is in the western B&R province. Starting with the 1869 Olighouse, Nevada earthquake, this belt has experienced nine GRE—an average of one every 15 yrs (9 events in 130 yrs). The most recent was the M 7.2 Fairview Peak and M 6.8 Dixie Valley earthquakes on Dec. 16, 1954. Interestingly, there were four separate GRE in northern Nevada in 1954, which marks a strong temporal cluster in the 130-yr long sequence of historic events. The high concentration of faulting in the CNSB, which includes about half of the 17 historic GREs for the entire B&R, does not characterize prehistoric times. Paleoseismic studies of individual faults in the belt show clearly independent times for their previous GREs (as far back as 40 ka), so the recent earthquake sequence in the CNSB may be unique or unprecented.

There are perhaps 1000 Quaternary faults within the B&R province and their characteristics range widely. The Wasatch fault zone and the eastern Sierra Nevada frontal fault zone (informal name) have slip rates that are perhaps 10 times higher than most IMW faults owing to their position at the B&R province's east and west margins. The interior faults of the province are typically moving at <0.2 mm/yr and most are late Quaternary (<130 ka), rather than Holocene or post glacial (<15 ka).

The 380-km-long Wasatch fault zone, subject of almost 20 years of paleoseismic research, appears to rupture in separate sections (or segments) that range from about 40-70 km in length. These B&R earthquakes are probably in the M7-7.5 range (Machette and others, 1991). On average, over the past 6,000 yrs there has been a rupture every 400 yrs on the central, more active portion of the fault zone, where individual sections rupture about every 2,000 yrs. Slip rates have been about 1-2 mm/yr for the past 15 ka, but appear to have been much lower during the late Pleistocene, perhaps as a result of crustal of loading by the 300-m deep Lake Bonneville (Machette and others, 1992). Today, the Wasatch fault zone is relatively aseismic, and has been since the region was settled 150 yrs ago.

Quaternary faults of the RGR of Colorado, New Mexico, west Texas, and northern Mexico have the general same characteristics as interior faults of the B&R. Some of the more prominent range-bounding faults, such as the Organ Mountains, Parajito, and Sangre de Cristo, have slip rates of 0.5-1.0 mm/yr (Machette and others, 1998), but most are <0.2 to as little as 0.01 mm/yr. These low rates and high RIs (50-100+ k.y.) mean that most faults have little impact on seismic-hazards assessments unless the window of consideration is quite long (*i.e.*, 2% probability in 1,000 yrs or a 50 k.y. window). The only historic GRE in the RGR was the 1887 Sonora earthquake (Mw 7.4), which formed a 90+ km long rupture. The penultimate rupture on this fault occurred at ≥100 ka.

**Continental intraplate tectonics**

The least active tectonic regime in the conterminous U.S. is the continental intraplate, which is underlain by stable cratonic rocks, several ancient rift systems, and the passive-margin of the Atlantic seaboard. The region is generally under compressional stress (Zoback, 1992). For our compilation, Crone and Wheeler (2000) examined 61 features in the Central and Easter U.S. that are of possible tectonic origin: they found only 10 features that have evidence of Quaternary tectonic faulting or deformation and another 10 that are of possible tectonic origin.

Several large intraplate earthquakes are documented in North America: the 1811-12 New Madrid earthquake sequence, the 1886 Charleston earthquake, and the 1989 Ungava earthquake in northern Quebec, Canada. Of these, the only one to produce a *bona fide* rupture was the $M_s$ 6.3 Ungava earthquake (Adams and others, 1992). Studies of the shear zone that ruptured during this earthquake indicate that brittle deformation (and by inference, prehistoric GRE) had not occurred in perhaps $10^9$yrs. The New Madrid sequence consisted of three M 7-8 earthquakes over the winter of 1811-12, and a modern-day recurrence of such an earthquake would be disastrous to St Louis, Memphis, and the surrounding region.

**Examples of intraplate faults and deformation zones.**

The New Madrid and Charleston seismic zones are the most active in the central and eastern U.S. and are the sources of the most significant historical earthquakes in the region. In both zones, little is known about the causative faults, but they are recorded by widespread liquefaction features such as sand blows. Recent and on-going paleoseismic studies of liquefaction features have greatly improved our knowledge of the recurrence of large earthquakes (M 7-8) in intraplate settings. During the late Holocene (past 3 k.y.), earthquakes large enough to cause liquefaction have occurred at intervals of several 100 to a few 1000 years. New geodetic and blind-thrust modeling suggests that uplift in the New Madrid area might be occurring at as much as 6 mm/yr—rates that are geologically unsupported. Likewise, sub-surface structural studies show that the rate of late Holocene deformation cannot have been sustained through the Quaternary because the underlying Cretaceous rocks are not extensively deformed. This contrast between the high rates of modern uplift and geologic evidence of low, long-term slip shows that either the deformation has only began recently, or that the temporal pattern of deformation is very episodic.

Two other intraplate faults merit discussion in North America: the Meers fault in Oklahoma and the Cheraw fault in Colorado, both of which are currently aseismic. The Quaternary scarp along the Meers fault is as much as 5 m high, and recent paleoseismic studies show that the most GRE occurred about 1.1-1.2 ka (Crone and Luza, 1990). This event was preceded by another GRE at 2.9-3.4 ka (Kelson and Swan, 1990), implying only 1.7-2.3 k.y. between these two events. However, the middle Pleistocene alluvium (>130 ka) is offset essentially the same amount as is lower Holocene alluvium (Crone and Luza, 1990). Thus, two GREs occurred on the currently aseismic Meers fault within the past 3,400 yrs, but these events were preceded by at least 100,000 yrs of tectonic quiescence (*i.e.*, no offset on fault).

The Cheraw fault in southeastern Colorado has sparse historical seismicity, yet has convincing geologic evidence of episodic rupturing. This 44-km-long fault displaces early(?) Pleistocene alluvium about 7-8 m vertically, which suggests a very low Quaternary slip rate (*i.e.* <0.01 mm/yr). Trenching suggests that its 3.6-m-high scarp was formed by two GRE between 10 and 30 ka and a third GRE around 8 ka (Crone and others, 1997). The Cheraw fault has an overall low Quaternary slip rate, but experienced a cluster of three GRE in a relatively short period of time (<22 k.y.).

Individual intraplate faults commonly show episodic earthquake behavior (clustering) and are blind, but they can cause large (M>7) earthquakes with RIs of 300-1000 yrs over geologically short-lived intervals (Table 1). However, when these clusters are 50-100 k.y. or more apart, the term "recurrence interval" may not be appropriate to use for recurrent faulting.

**Conclusions**

Regional comparisons between major faults in transpressional, compressional, extensional, and intraplate regimes show important differences in styles of deformation, slip rates, recurrence intervals, and patterns of episodic behavior. Quaternary deformation in transpressional and compressional regimes (mainly west coast) is accomodated mainly by strike-slip and thrust movement on faults that have slip rates 1-2 orders of magnitude greater than those in the extensional Intermountain West and more stable conpressional intraplate regions to the east. Recurrence intervals in the transpressional and compressional regimes of the west coast are accordingly shorter, with the exception of some intraplate faults that show evidence for clustered short-term behavior. The majority of deformation within the Intermountain West is associated with slow slip (<0.2–1.0 m/yr) normal faults that have recurrence intervals of thousands to ten of thousands of years, whereas the more sparse intraplate faults to the east are primarily strike slip or thrusts having very low long-term slip rates but variable recurrence intervals.

Our 75 percent complete ILP compilation of Quaternary faults and folds provides robust geologic and paleoseismic data for seismic-hazards assessments. In addition, since it is being developed with GIS and relational database software, it is easily updated and accessed via the Internet.

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