Map and data for Quaternary faults and folds in Washington State

By David J. Lidke, Samuel Y. Johnson, Patricia A. McCrory, Stephen F. Personius, Alan R. Nelson, Richard L. Dart, Lee-Ann Bradley, Kathleen M. Haller, and Michael N. Machette

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Introduction

The "World Map of Major Active Faults" Task Group is compiling a series of digital maps for the United States and other countries in the Western Hemisphere that show the locations, ages, and activity rates of major earthquake-related features such as faults and fault-related folds. The companion web-based database includes a review of published information on these seismogenic features. The Western Hemisphere effort is sponsored by International Lithosphere Program (ILP) Task Group II-2, whereas, the effort to compile new maps and the Quaternary fault and fold database for the United States is funded by the Earthquake Reduction Program (ERP) through the U.S. Geological Survey. The maps and database represent a key contribution to the new Global Seismic Hazards Assessment Program (ILP Task Group II-0) for the International Decade for Natural Disaster Reduction. This map contribution, which shows known and probable Quaternary faults and folds in Washington State, is the tenth in a series of State and regional compilations that are planned for the U.S. Published compilations of West Texas, New Mexico, Wyoming, Montana, Oregon, and the central and Eastern U.S. are available from the U.S. Geological Survey (Collins and others, 1996 #993; Machette and others, 1998 #2848; Haller and others, 2000 #1750; Crone and Wheeler, 2000 #4359; Machette and others, 2001 #5030; Personius and others, 2003 #6313); Arizona is available from the Arizona Geological Survey (Pearthree, 1998 #2945); Colorado is available from the Colorado Geological Survey (Widmann and others, 1998 #3441); and Utah is available from the Utah Geological Survey (Black and others, 2003 #5828).

This compilation for Washington State is presented as an online, digital map product in *Adobe Acrobat pdf format and it is linked to the web-based Quaternary fault and fold database of the United States. The online database provides a catalog of referenced data on a variety of geographic, geologic, and paleoseismologic parameters associated with the features shown on the map. The authors of this map compilation are responsible for organizing and integrating Washington State products under the national project, including the coordination and oversight of contributions from others (Lidke, Johnson, McCrory, Personius, and Nelson), digitization and manipulation of map data (Dart), map design and layout (Bradley), and database design and management (Haller and Machette). Version 1.0 of the Quaternary fault and fold database of the United States (http://qfaults.cr.usgs.gov/) was recently released (see also, Machette and others, 1999 #4783; Haller and others, 1999 #4784), and existing data shown in this Washington State map compilation are included in version 1.0 of the database.

This map compilation for Washington State, referred to elsewhere herein as the "the map" or "this map" is intended to be a companion publication to the web-based Quaternary fault and fold database of the United States, referred to elsewhere herein as "the database." Recently published State and regional map-compilation products noted above, are similarly companion products to the database. This map is the first of these State and regional products that post-dates the initial release of the database (version 1.0). The previously released State and regional map compilations included lengthier pamphlets, which contain description, discussion, and data for faults and folds included in those compilations. Inclusion of substantial supporting information in pamphlets of the previous map compilations was necessary, because at that time the database had not been released and could not serve as the main source of supporting information and data for structures presented in those compilations. Inasmuch as supporting information and data are now available in the online database for Washington State and these other States and regions, that information is not duplicated and included herein. The web address to the database (shown above) provides a link to information and data, other online maps, and downloadable ARC/GIS files of map data.

In addition to showing Washington State and offshore regions west and northwest of the State, this map also shows adjacent parts of Oregon, Idaho, and British Columbia. The map shows the continuations of Washington State faults and folds that extend into and offshore of northern Oregon, and shows other northern Oregon structures that do not extend into Washington State and that are not numbered on this map. The faults and folds shown in and offshore of northern Oregon are also shown, completely numbered, and described in a map compilation for Oregon (Personius and others, 2003 #6313), which is similar to this one, and shown and described in the online database.

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No faults or folds are shown in the part of western Idaho that is included on this map. At this time, our preliminary compilation for Quaternary faults and folds of Idaho does not identify any Quaternary structures in the part of western Idaho shown on this map. Although Quaternary faults and folds have been identified on Vancouver Island, British Columbia, this map and the database only include the continuations of some speculative Quaternary faults in Canadian waters of the Strait of Juan de Fuca, south of Vancouver Island. This Washington State compilation and the database do not evaluate evidence for the presence or absence of Quaternary faults and folds elsewhere in and offshore of Canada. Consequently, the absence of faults and folds in the region of southwestern Canada shown on this map, indicates only that this region was not evaluated for this compilation and the database and it is not intended to imply a known absence of Quaternary structures in that region of Canada.

Strategy for Map and Database

The primary intent of this map compilation and the database is to summarize paleoseismologic data and geologic information on known and suspected Quaternary faults for use in seismic-hazard investigations and evaluations. Paleoseismic studies, which evaluate and document the history of surface faulting and deformation along structures with evidence of Quaternary movement, provide a long-term perspective that augments the short historic records of seismicity or geodetically measured strain in many regions. In particular, the frequency and location of large-magnitude earthquakes in many parts of the U.S., including Washington State, are poorly defined by the historic record of seismicity. Consequently, the long-term perspective provided by a catalog of the seismogenic characteristics of prehistoric faults is vital to improving seismic-hazard assessments in all regions, not just those having low to moderate levels of historic seismicity.

This map and the database identify and catalog faults and folds that show evidence for Quaternary (<1.6 Ma) surface-rupturing fault offsets or surface-deforming folds. Typically, deformed Quaternary rocks or sediments provide the principal evidence for Quaternary surface-deforming events. Therefore, Quaternary surface-deforming faults and folds may have been overlooked in areas of Washington State that lack Quaternary strata and datums, and overlooked in other areas where young Quaternary deposits or surficial processes have destroyed, buried, or otherwise obscured evidence for older Quaternary surface-deforming events. This map and the database do not attempt to characterize the magnitude or intensity of earthquakes, which probably accompanied tectonic events that produced the identified Quaternary fault offsets and folds. For Washington State there is no documented evidence of surface-rupturing fault offsets or of surface folding during historical earthquakes (Rogers and others, 1996 #4191). Small-magnitude to relatively large magnitude, historical earthquakes and associated ground shaking are, however, well documented in Washington State. Ground shaking from some of the historical earthquakes caused significant damage and loss of lives. Although surface deformation along fault and folds is not known to have resulted from these and other historical earthquakes, ground shaking triggered ground failures during some of the historical earthquakes. These historic, earthquake-induced ground failures include landslides, surface cracks, liquefaction, and ground settlement, which locally contributed substantially to damages and losses caused by some of the historical earthquakes. The locations and characteristics of ground failures produced by seismic shaking from historic earthquakes in Washington State, however, do not identify surface deforming events along any specific faults or folds. Consequently, the locations of ground failures produced by historic seismic shaking are not shown on this map and they are not cataloged in the database. Ground failures resulting from seismic shaking during the 1949, 1965, and 2001 deep earthquakes beneath the Puget Lowland region, are documented and described in greater detail elsewhere (e.g., Chleborad and Schuster, 1998 #6719; Troost and others, 2001 #6721; Walsh and others, 2002 #6720) and these relatively large and deep historic earthquakes are also briefly discussed below.

The largest magnitude Washington State historical earthquakes include the 1949 Olympia earthquake (M 7.1), the 1965 Seattle-Tacoma earthquake (M 6.5), and the 2001 Nisqually earthquake (M 6.8). These and several other historical earthquakes in Washington State had deep epicenters at depths of 30-50 km or more below the Puget Lowland. These depths imply that the epicenters were located within the Juan de Fuca plate that underlies a major thrust fault or zone of thrust faults called the Cascadia subduction zone [781]. This subduction zone defines the fault boundary between Juan de Fuca plate and the North American plate that overrides and overlies it. The Juan de Fuca plate underlies the North American plate at a depth of about 25-30 km beneath much of the Puget Lowland. Deep earthquakes in the Juan de Fuca plate beneath western Washington State, appear to have a high probability of damaging ground shaking about every 30-50 years or so (e.g., Rogers and others, 1996 #4191). Their lack of manifestation as surface faults and folds, however, prohibits their inclusion and characterization for this map and the database. These relatively frequent deep earthquakes beneath western Washington State, as well as the potential for a great earthquake (M >8.0) along the Cascadia subduction zone [781], are discussed in much more detail in Rogers and others (1996), but they are beyond the scope of this map and the database.

This map and the database do present and catalog evidence for prehistoric to late Quaternary (<1.6 Ma) earthquakes that probably coincided with surface offsets along faults and or folding at the surface. A surface-rupturing event along the Seattle fault zone [570] is known to have occurred as recently as about 1000 years ago (e.g., Bucknam and others, 1992 #602; Atwater, 1999 #4715; Nelson and others, 2003 #5868). Structures shown on this map and cataloged in the database have documented evidence for pre-historic to late Quaternary (<1.6 Ma) surface-deforming events, which probably also record relatively large magnitude earthquakes with shallow epicenters (<25 km). An association of shallow epicenters with these events would imply greater intensities of ground shaking and damage than would be produced by deep earthquakes of similar magnitude (e.g., Rogers and others, 1996 #4191). Damage producing deep earthquakes described above, apparently occur more frequently than do the surface-rupturing events. The potential for significant damages and losses from shallower surface-deforming events, however, warrants the attention that is focused on faults and folds shown on this map and cataloged in the database, which show evidence for Quaternary surface-deforming events.

The map and database formats were originally designed to summarize data for the few well-studied faults that are present in the United States. Because the bulk of seismogenic structures have not been well characterized, the database is of unequal detail and, for many structures, is incomplete. For example, many unnamed faults have little data and sparse descriptions. Furthermore, mapping and studies of Quaternary structures in Washington State have been uneven, likely resulting in inadvertent biases in the distribution and characterization of known structures. Nevertheless, the fault map and database provide the best presently available basis for assessing potential seismic sources. Because most of the fault and fold data comes from reconnaissance studies, future more detailed field studies may yield more complete characterization and require modification of the current compilation. Such changes will probably be made to the web-based database, rather than as subsequent Open-File Reports.

The map shows faults and folds with evidence of Quaternary activity in Washington State, and includes a table showing the timing of most recent movement, sense of movement, and slip rate for each structure. The information shown in the map tables is discussed in more detail in the online database. Many fault and fold traces were taken from existing 1:250,000-scale, geologic map compilations of Washington State (Walsh and others, 1987 #3579; Stoffel and others, 1991 #5667; Schuster and others, 1997 #3760; Dragovich and others, 2002 #5715). A few traces were taken from more detailed, larger scale studies, and compiled on 1/2° x 1° (1:100,000-scale) or 1° x 2° (1:250,000-scale) topographic maps. As such, most fault and fold traces shown on this map and in the online database, probably are accurate at 1:250,000 and smaller scales. Some traces, principally those shown in the Seattle region inset map, may be accurate at 1:100,000 and smaller scales. The traces were digitized and geo-referenced for use in *Arc/Info—Geographic Information System (GIS) software that permits rescaling, output in a wide variety of map projections, and attribution (assigning colors, line weights, and symbols). The Arc/Info files were used to create the PDF file for this map. The original ARC/Info files can be viewed and downloaded from the database website (http://qfaults.cr.usgs.gov/). In addition to location and style of faulting, the map shows the time-range category of most recent movement and slip-rate category for each structure. These known or assigned characteristics are also shown in table 1. These data, as well as name and affiliation of the compiler, date of compilation, and other geographic, geologic, and paleoseismologic parameters are presented in more detail in the database. Published maps and reports and publicly available (NEHRP contract reports, theses, etc.) information are the primary sources of data used to compile this map and the corresponding database information for Washington State. Citations are in standard USGS format, with the exception that we include a database reference number (e.g., Haller and others, 1993 #644). This reference number allows us to omit the traditional alpha character for authors having multi-year publications (*e.g.*, 1988a, b).

The presentation of Quaternary faults and folds shown on this Washington State map differs in some respects from their presentation in online maps that are included in the database. These structures, however, are identical in location, name, and assigned fault number on this map and maps in the database. The main differences are that this map shows more detailed topographic (DEM) and cultural features (cities, roads, and etc.) data on its base map, and shows symbology to indicate the sense of offset along faults, the geometry of folds, and the continuity of surface expression of individual faults and folds. This map also more precisely shows the locations of detailed

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paleoseismology study sites (*e.g.*, coastal and trench study sites). The interactive map in the database also includes symbology information for individual faults and folds, however, that information is in tabular text format and not visually represented on the interactive map. Fault and fold symbology shown on this map, are briefly described in the map symbols legend and terms used in the legend are described in the glossary present in the online database. In addition to known surface faults, some Quaternary faults that are suspected or inferred from subsurface or other data are shown as dotted lines (*i.e.*, buried structures). The locations, extent, and characteristics of the offshore faults are based principally on interpretation of seismic-reflection data. Physical inspection of the seafloor and these offshore features is not generally feasible. Consequently, detailed subdivision of the surface expression and continuity of offshore features did not seem reasonable for this map and these offshore faults and offshore parts of faults are mostly shown on the map as solid lines. Continuity is commonly more apparent in offshore seismic data than it is for many onshore continuations of faults that occur in glaciated and heavily vegetated terrain (e.g., southern Whidbey Island fault zone [572]). The solid traces shown for these offshore faults only implies that the existing data suggests that these faults are continuous to relatively continuous features that may, or may not, have surface expression along the seafloor. Although folds are associated with some of these offshore faults, the traces of offshore folds are not shown in this compilation or in the database.

The timing of most recent fault movement (*i.e*., surface rupture) is depicted on this map as one of five categories: historic (ca. <150 yr ago), Holocene and latest Pleistocene (<15 ka), late Quaternary (<130 ka), late and middle Quaternary (<750 ka), and Quaternary (<1.6 Ma). However, the historic age category is not used on this map or in the database for Washington State, because, as previously noted, no faults or folds in Washington State are known to have deformed the surface during historic time. These categories define a maximum age for the time of most recent movement without constraining a minimum time that may require more detailed studies. This strategy allows time-range estimates where published data are sparse or where there are minor conflicts in evidence for timing. For example, if Holocene (<10 ka) movement is suspected but only late Pleistocene (10-130 ka) movement is documented, then the inclusive late Quaternary (<130 ka) category is assigned as the time of the most recent movement. Quantifying the age of most recent structural activity, however, can be hampered by the lack of Quaternary strata or datums. Structures with known late Tertiary or older (>1.6 Ma) movement are not shown unless there is sufficient possibility of Quaternary movement based on physical evidence (*e.g.*, geomorphology, offset undated surficial deposits, etc.). Furthermore, faults or folds lacking evidence for Quaternary surface-deforming activity, even those that show alignment with the occurrence of seismicity at depth, are not shown on this map or cataloged in the database. A few of these structures that align with seismicity are, however, listed in table 2 on the map and briefly discussed as Class C structures in the database; the Class C structure category is described below. This conservative depiction of faults and folds yields a map with defensible potential sources of future ground rupturing based on Quaternary history (last 1.6 million years). A less conservative depiction would yield a “neotectonic” map that may yield overly high seismic-hazard assessments.

We graphically represent slip rate on the map. Fault slip rates and fold uplift rates are delineated by line thickness categories that encompass all rates on a national scale. Four slip-rate categories have been defined for this project: less than 0.2 mm/yr, 0.2-1 mm/yr, 1-5 mm/yr, and greater than 5 mm/yr. These broad categories segregate most intraplate structures (<1 mm/yr) from major plate-bounding structures (generally >5 mm/yr). In Washington State, faults and folds that fall in the >5 mm/yr and 1-5 mm/yr categories are those associated with the Cascadia subduction zone [781], a plate boundary offshore of northern California, Oregon, Washington, and southern British Columbia. All other faults/folds are intraplate structures and have published or inferred rates of less than 1.0 mm/yr. Most have inferred slip or uplift rates of <0.2 mm/yr. If no published slip rates exist (*i.e*., "unknown"), we assign the fault to a slip-rate category as determined from less quantitative data, such as geomorphic expression or similarity to nearby structures with known slip rates. Where available, the length of time for which the estimated slip rate applies is listed in the database. A variety of geomorphic and geologic relations can be used to place a fault in its most likely age category. For example, a normal fault that does not cut latest Pleistocene (10-15 ka) deposits probably has an average slip rate of less than 1 mm/yr, because during this elapsed time interval at least 10-15 m of potential slip would be expected to accumulate at a rate of 1 mm/yr. An exception to this generalization is a fault that shows evidence of temporal clustering; that is, several closely spaced events separated by longer intervals of tectonic quiescence. In such cases, the average slip rate could be considerably less than the slip rate of a time interval that mostly or entirely coincides with a period of clustered earthquakes. Cases such as these are becoming more documented in the literature as researchers conduct more detailed paleoseismic studies.

The database includes fields that summarize supporting information on the previously discussed parameters portrayed on the map, as well as includes fields for other descriptive, geologic, and paleoseismologic parameters and information not depicted on the map. The descriptive information includes fault/fold name and number, a synopsis, compilation information, and quality of structure location. Because the overall project will include data from the entire United States, the database assigns each structure a unique number. In the database text, structure numbers are enclosed by square brackets, such as [568]. Names come from the literature and from common usage. Although some structures in different regions have the same or similar names, no attempt was made to re-name them to avoid duplications. Geologic data include geologic setting, sense of movement, dip angle and direction, geomorphic expression, age of faulted deposits, and length and average strike (azimuth) of the structure, all in descriptive form. Paleoseismologic data include descriptions of published detailed studies (*e.g.*, trenching) and estimates of time of most recent prehistoric faulting, recurrence interval(s), and slip rate(s). Information and data categories (field names) are defined in the Glossary in the database (see also, general guidelines published in Haller and others (1993 #655)).

We define four categories of faults and folds in the database (Classes A-D; see also, definition of "fault class" in Glossary of the online database), based on the documented evidence for Quaternary tectonic movement. Class A and B structures each have an assigned unique number. These structures are shown on this map and maps included in the database, listed in table 1, and described in the database as simple, sectioned, or segmented structures (see below). Class A features are structures of tectonic origin with documented evidence of Quaternary displacement. Class B features are either (1) structures of non-tectonic origin, such as faults associated with volcanic activity, or (2) tectonic faults with equivocal evidence of Quaternary displacement. A third group of structures, Class C and D features, we have intentionally excluded from this map and maps in the database. Class C and D structures are, however, listed in table 2 and briefly discussed in the database. In general, faults or folds assigned Class C and D designations consist of structures in Washington State, which have been inferred or suggested to show evidence of Quaternary surface deformation in the existing literature. Our assignment of Class C or D designations to these structures mostly indicates that we considered the proposed evidence to be too speculative to include these structures in either the Class A or B categories. In some cases, however, our Class C or D assignments are based mostly on later studies that dispute the previously proposed evidence for Quaternary activity. Faults or folds that have not at least been inferred or suggested to show evidence of Quaternary surface deformation in the existing literature are not included in the Class C and D fault categories. Class C features, are those where geologic evidence is insufficient to demonstrate either (1) the existence of a tectonic fault, or (2) Quaternary slip or deformation associated with a known fault. Eleven features in Washington State are assigned to this category. These features are mostly structures associated with pre-Quaternary tectonism, volcanic activity, or are faults included in previous compilations where evidence of displacement in Quaternary deposits is not compelling. Class "D" features are those where geologic evidence demonstrates, or strongly implies, that the feature is not a tectonic fault; this category includes features such as joints, landslides, erosional scarps, and lacustrine or marine shoreline features. Only one Class D feature is considered in this compilation.

Map compilations such as this one, and supporting information in the database, allow comparisons of spatial and temporal patterns of faulting at local, regional, and national scales. However, a database is most useful as a tool in this manner if it represents a systematic and comprehensive collection of data. The available data from mapping and studies of Quaternary structures in Washington State are uneven, however, and the database is neither entirely systematic nor entirely comprehensive. With this in mind, we favor published or publicly accessible data and reference it as completely as possible. We try to include all pertinent data, especially where data conflict. Where multiple interpretations exist in the literature, we use a hierarchy that defines what data will be presented in the primary database fields in order to achieve consistency in fault/fold treatment. We give highest priority to fault-related studies, particularly those addressing the Quaternary history of a fault (*i.e.*, paleoseismic investigations), over more general geologic studies (*e.g.*, bedrock mapping). In most cases, more recent studies are given priority, although older studies can be quite useful and accurate. The locations of faults and folds based on detailed mapping (*e.g.*, 1:24,000 scale) are given priority over locations mapped with less detail (*e.g.*, 1:250,000 scale). Even though we give the most weight to recent studies of Quaternary faulting (*i.e.*, paleoseismology), interpretations based on other types of studies are summarized in the "Comments" fields in the database.

The vast majority of the Quaternary structures or groups of structures in Washington State (table 1) have been examined by limited investigations. In order to accommodate large differences in the level of study from fault to fault, we established three types of fault descriptions to simplify data compilation and readily convey the level of current knowledge (Haller and others, 1993 #655). All structures plotted on the map and listed in table 1 are described in the database as simple, sectioned, or segmented structures. In general, "simple" faults or folds are poorly known, have had few or no paleoseismologic studies, are characterized by a single time datum and slip- or uplift-rate category for most of their length, and are typically less than about 30 km in length. At the other end of the spectrum are segmented structures—those well-studied and well–known faults or folds that are comprised of multiple seismogenic or structural parts that may act independently of one another during surface-rupturing earthquakes. For example, by our standards and definitions (Haller and others, 1993 #655), the timing of surface-rupturing events on segments of a fault must be well established through trenching and dating studies or the presence of historical surface ruptures. There should be supporting geomorphologic and geologic data (scarp morphology, stratigraphic control on times of faulting, geologic structures that may control physical segmentation, etc.). In some cases, pronounced contrasts in the geomorphic expression of faulting or folding along strike combined with paleoseismic studies that define the chronology of the youngest events on the faults or folds are sufficient to permit discussion of the structure in terms of segments. None of the faults and folds included in this Washington State compilation have the necessary detail to be described as segmented structures. We instead categorize some of the longer, or more complex, faults and folds of Washington State as sectioned structures. It is possible that parts of some of these sectioned structures behaved as segments during past events, but documented evidence for such behavior is lacking. This third category (sectioned structures) is used to characterize faults or folds as discrete strands or parts, without inferring rupture independence. Sections may be defined on the basis of relative-age criteria, fault or fold geometry, the presence or absence of morphologic differences in fault scarps, paleoseismic data, or from other geologic or geophysical data. Several of the faults and folds included in this compilation for Washington State are described as sectioned structures. The simple structural features are shown on the map and listed in the database by a three-digit numeric identifier (*e.g.*, [560]); whereas, the sectioned structures are identified by an additional lowercase alpha character (*e.g.*, [845a, 845b, 845c], etc.). The alpha characters (a,b,c etc.) are unique to each of the sections; "a" is commonly assigned to the northernmost or westernmost section and other sections sequentially lettered moving southward or eastward, respectively.

Synopsis of Quaternary Faulting and Folding in Washington State

Sources of Data

There are several existing statewide and regional compilations of faults and folds for Washington State and adjacent areas offshore. Some of these compilations include both Quaternary and pre-Quaternary structures, but do not distinguish features that show evidence for Quaternary activity from those that do not (e.g., Newcomb, 1970 #3761; McLucas, 1980 #6205). Other compilations, however, are specifically focused on Quaternary structures or identify structures that show evidence for Quaternary activity (e.g., Howard and others, 1978 #312; Gower and others, 1985 #4725; Wagner and others, 1986 #5670; Wagner and Tomson, 1987 #6249; Tolan and Reidel, 1989 #3765; Rogers and others, 1996 #4191; Johnson and others, 2000 #4750). Most of these compilations provided information and data that are incorporated in this map compilation and the database. A 1:250,000-scale seismotectonic map of the Puget Sound region by Gower and others (1985 #4725), shows and briefly describes 41 sites where deformation of Quaternary sediments can be seen or inferred. Many of these sites probably record Quaternary tectonic events and are correlated herein and in the database with known or inferred faults. Some of these sites, however, may reflect deformation related to Pleistocene continental glaciation or cannot at this time be correlated with a specific fault or fold. Consequently, those sites are not shown on this map or discussed in the database. The most comprehensive previous compilation of Quaternary structures of Washington State, is the 1:2,000,000-scale map of known and suspected Quaternary faults in the Pacific Northwest by Rogers and others (1996 #4191), which incorporates information from other previous regional compilations and provides a list of references for the faults shown.

Much of our information comes from geologic investigations that have been conducted at differing scale and with differing focus. Numerous consulting reports, many related to seismic risk studies (e.g., Geomatrix Consultants Inc., 1990 #5550), are incorporated in this compilation. Few of these seismic risk studies, however, include detailed paleoseismologic investigations. Recent and ongoing paleoseismologic investigations are concentrated mostly in and near the Puget Lowland urban areas (see inset map) and along and near the coast of western Washington State. Much of the information presented, however, is derived from maps and other geologic investigations that lack quantitative evidence for Quaternary deformation along specific faults and folds.

Submerged faults shown in the Puget Sound, Strait of Juan de Fuca, and Pacific Ocean west Washington State, are based principally on interpretation of seismic-reflection data of varying resolution and coverage. Locations and data for faults shown in the Straight of Juan de Fuca and northern Puget Sound are mostly from investigations and regional seafloor maps published by Wagner (1987 #6249) and Johnson (2000 #4750). Several faults in the eastern part of the Straight of Juan de Fuca and in Puget Sound, such as the Seattle fault zone [570] and Southern Whidbey

Island fault zone [572], have known onshore continuations and much more published information. The compilation shown on this map and in the database is incomplete for large areas of the Pacific Ocean region shown west of Washington State. A preliminary map of seafloor geology of the continental shelf and upper continental slope west of Washington State (Wagner and others, 1986 #5670), shows offshore faults and folds in the Pacific Ocean areas offshore of Washington State that are not compiled on this map and maps in the database. Most of the faults identified as showing evidence for Quaternary offset on that seafloor map by Wagner and others (1986 #5670), were later recompiled on the Quaternary fault map of the Pacific Northwest by Rogers and others (Plate 1, 1996 #4191). The locations and ages of faults shown on the Wagner and others (1986 #5670) map, however, are based mainly on interpretation of relatively sparse seismic-reflection data and more recent investigations suggest noticeably different locations and patterns of faults and folds in those offshore areas (Goldfinger and others, 1997 #4090; McCrory and others, 2002 #5864). This map compilation and the database include numerous faults on the central to southern inner continental shelf west of Washington State, which are based principally on more recent investigations reported in McCrory and others (2002 #5864). More recent interpretative maps of faults and folds in the outer continental shelf and slope west of Washington State include the offshore areas not compile d on this map, but currently they are published as page-size illustrations and not available at larger scales needed for this compilation (Goldfinger and others, 1997 #4090). Areas offshore of western Washington State lacking more recent data and interpretation at a useable scale were not compiled for this map and version 1.0 of the database.

The Cascadia subduction zone [781] is the principal structural feature offshore of western Washington State and is also the principal structural feature of this region. It is a major plate boundary offshore and beneath British Columbia, Washington, Oregon, and California. The seafloor trace of this subduction zone is shown offshore of southern Washington and northern Oregon on this map and it continues to both the northwest and south of the map area. Along and near the coast of Washington and northern Oregon, several coastal paleoseismology study sites (*e.g.*, 781-23) are shown on this map and in the database. These coastal study sites document evidence related to ancient earthquakes along the subduction fault and they are discussed in the database. Similar coastal paleoseismology study sites are shown on the map in the Puget Sound region. These sites mostly document studies related to the Seattle fault zone [570], Tacoma Fault [581], and the southern Whidbey Island fault zone [572], however, some of these sites may also document tsunamis generated by earthquakes along the Cascadia subduction zone [781].

It should be emphasized that investigations of Quaternary faults and folds in Washington State are at an early stage, particularly offshore and in western Washington State where tectonic landforms have been difficult to recognize and document because they are covered by sea water or dense vegetation. There are no doubt, numerous Quaternary structures yet to be identified, and more detailed studies of known and suspected Quaternary faults and folds are needed. Airborne Laser Swath Mapping (ALSM), also known as Light Detection And Ranging (LIDAR), with its ability to penetrate forest canopies and produce high-resolution topography, provides an important new tool for neotectonics investigations (e.g., Haugerud and others, in press #5867). For example, Nelson and others (2003 #5868) document 3 or 4 ground-rupturing events on an ALSM-recognized backthrust in the Seattle fault zone [570] in the last 2500 years, a significant new contribution to understanding regional earthquake hazards.

Overview of Quaternary Tectonic Setting

Northeast-directed oblique subduction of the Juan de Fuca plate beneath North America has created a complex, seismically active convergent margin in the Pacific Northwest of the United States and Canada (“Cascadia”), of which Washington State is a part. Convergence, about 35-40 mm/yr, is the driving force for northward migration of a “forearc sliver” and for elastic strain accumulation in the North American plate (Wells and others, 1998 #4742). Other important tectonic processes impacting Washington State include dextral shear and possible clockwise rotation associated with the northward movement of the Pacific plate relative to North America. The result of these tectonic processes is partitioning of Washington State into several discrete geologic provinces (fig. 1): (1) the Olympic Mountains, continental shelf and slope (e.g., Tabor and Cady, 1978 #6221; Snavely, 1987 #6311); (2) the Coast Range (e.g., Wells and Coe, 1985 #6718; Babcock and others, 1992 #6245); (3) the Puget Lowland forearc basin (e.g., Johnson and others, 1996 #4751; Wells and others, 1998 #4742); (4) the Cascade volcanic arc (e.g., Walsh and others, 1987 #3579; Dragovich and others, 2002 #5715); (5) the northern Washington pre-Tertiary highlands (e.g., Misch, 1966 #5696; Stoffel and others, 1991 #5667; Tabor, 1994 #4762), and (6) the Columbia basin (e.g., Newcomb, 1970 #3761; Reidel and others, 1994 #3539).

Washington’s offshore continental shelf and slope is bounded to the west by the Cascadia subduction zone [781], a boundary between the North American and Juan de Fuca plates. The shelf is underlain primarily by variably consolidated Cenozoic material that has been scraped off the subducting Juan de Fuca plate and accreted to the continental margin. These accreted rocks have undergone dramatic Neogene uplift in the Olympic Mountains (Tabor and Cady, 1978 #6221; Brandon and Vance, 1992 #5863). Numerous Quaternary structures have been documented in this province (e.g., McCrory, 1997 #6323; McCrory and others, 2002 #5864), but historic earthquakes are few and recorded microseismicity is relatively minor. Several great earthquakes, most recently in AD 1700 (Satake and others, 1996 #6207), have occurred along the subduction zone beneath this western province. Atwater and Hemphill-Haley (1997 #4216) estimate an average recurrence of about 500-540 years over the last 3,500 years for these plate-boundary events. On its eastern and northern boundary, this geologic province is in thrust contact with Eocene marine basaltic rocks of the Crescent Formation (e.g., Tabor and Cady, 1978 #6221; Dragovich and others, 2002 #5715).

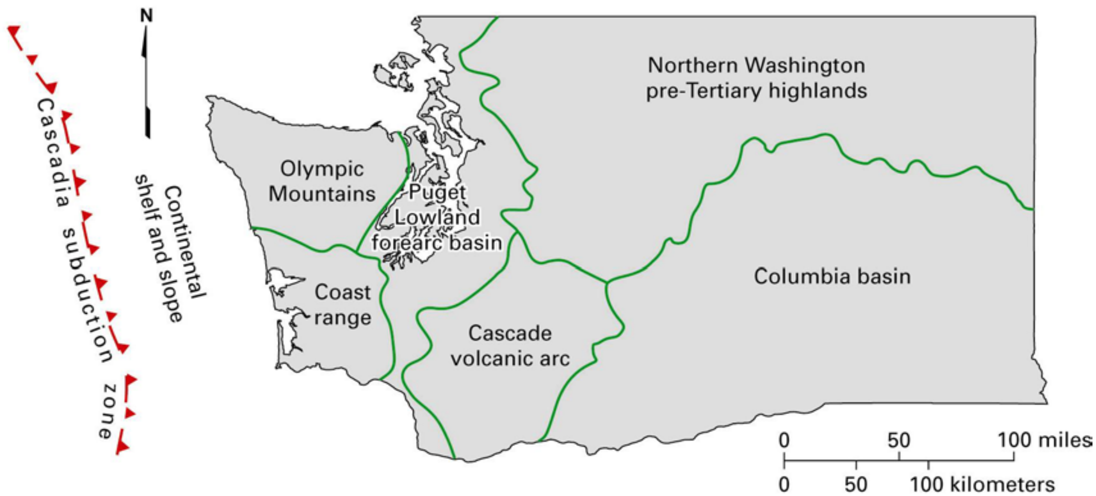

Figure 1.-Washington State Geologic provinces

The Coast Range province occupies southwest Washington State, and is located south of the Olympic Mountains and west of the Puget Lowland. This province and the Coast Range, extend south into western Oregon. The Crescent Formation (Eocene), the thick basement to this province, is overlain by mainly marine forearc-basin deposits (Rau and Johnson, 1999 #6717). The Coast Range is cut by numerous Cenozoic faults (e.g., Walsh and others, 1987 #3579). However, historic seismicity and recorded microseismicity are relatively sparse, and Quaternary activity has been documented on only a few structures.

The Puget Lowland province, largely covered by Quaternary glacial deposits, is part of a large, segmented forearc basin that extends from central British Columbia to southern Oregon. The northern part of this province, extending from Olympia to the international border, is the site of highly concentrated microseismicity in Washington State. Recent geophysical and paleoseismologic studies have documented several Quaternary faults, many with late Holocene (ca. <3 ka) offsets. These faults include the Seattle fault zone [570], the southern Whidbey Island fault zone [572], the Tacoma fault [581], the Utsalady Point fault [573], the Strawberry Point fault [571], and the Devils Mountain fault [574]. The Puget Lowland overlies the buried tectonic boundary between Eocene marine basalt basement of the Coast Range and pre-Tertiary basement of the Cascade Range, defining the eastern margin of the northward-migrating forearc sliver (Johnson and others, 1996 #4751). GPS data suggest north-south crustal shortening rates of about 4-7 mm/year across the central and northern Puget Lowland (e.g., Miller and others, 2001 #4732).

The central and southern Puget Lowland is bounded to the east by the Cascades volcanic arc province, composed largely by Cenozoic volcanic rocks. Quaternary stratovolcanoes include Mount Rainier, Mount St. Helens, and Mount Adams. Recorded seismicity has been concentrated on the north-trending Saint Helens' and West Rainier zones (Weaver and Smith, 1983 #938; Stanley and others, 1996 #5865), however, definitive evidence for Quaternary surface-rupturing earthquakes has not been documented along either zone.

The northern part of the Cascade Range in Washington State is underlain mainly by pre-Tertiary rocks and is here considered part of the northern Washington pre-Tertiary highlands. This mountainous region of pre-Tertiary rocks also contains scattered patches of Cenozoic volcanic rocks and Quaternary stratovolcanoes that include Mount

Baker and Glacier Peak. As shown in figure 1, this province extends west-northwest from northeast Washington State to the Puget Lowland. Although not portrayed in figure 1, pre-Tertiary rocks of this province are also present beneath the northern part of the Puget Lowland and extend farther west-northwest to Vancouver Island (Canada), where they form highlands and a buttress to the northward-migrating forearc sliver described above. This buttress may have considerable significance in focussing seismicity (Wells and others, 1998 #4742; Johnson and others, 2001 #4749). The northern Washington pre-Tertiary province is cut by numerous faults, however documentation of Quaternary activity is negligible. The largest known historic crustal earthquake ($M \geq 7$) occurred on an unknown fault in the North Cascades in 1872. The exact location, depth, and magnitude of this event have not been conclusively determined (Bakun and others, 2002 #6227).

The Columbia basin province lies east of the Cascades volcanic arc province and south of the pre-Tertiary province, occupying much of southeast Washington State. The Columbia basin is underlain by Miocene flood basalts, which cover numerous faults and folds extending south or east from the Cascades and northern Washington pre-Tertiary provinces. Several Quaternary faults have been documented in the Yakima fold belt (e.g., Reidel and others, 1989 #5553; 1994 #3539) in the southwestern part of the Columbia basin. These structures and seismicity and microseismicity in this region appear to be kinematically linked to the somewhat enigmatic, northwest-trending Olympic-Wallowa lineament (Raisz, 1945 #3509). The northwest-trending Wallula fault system [846] shows evidence of Quaternary activity and coincides with the southern part of this lineament in the Yakima fold belt. Other northwest-striking faults that show evidence of Quaternary deformation are also mapped along the Washington-Oregon border west of the Wallula fault system. In the southeast corner of Washington State, north- to northeast-striking faults of the Hite fault system [845] show evidence of Quaternary activity and occur partly in the Blue Mountains. The Blue Mountains are a more mountainous, deeply dissected part of the Columbia basin, which is structurally characterized as a northeast-trending, late Tertiary anticlinorium (e.g., Reidel and others, 1994 #3539).

This database includes descriptions of Quaternary faults and folds and several of these structures have their most recent activity in the late or latest Quaternary (<130 ka). The most active structures include the Cascadia subduction zone [781], and faults and folds in the Puget Lowland and Yakima fold belt. Given their proximity to population centers, Puget Lowland structures such as the Seattle fault zone [570], southern Whidbey Island fault zone [572], and Tacoma fault [581], probably present the greatest seismic risk.

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List of Contributing Individuals

Richard J. Blakely
U.S. Geological Survey
P.O. Box 94025, Mail Stop 989
Menlo Park, CA 94025
phone: (650) 329-5316
e-mail: blakely@usgs.gov

Lee-Ann Bradley
U.S. Geological Survey
P.O. Box 25046, Mail Stop 966
Denver, CO 80225-0046
phone: (303) 273-8613
e-mail: bradley@usgs.gov

Thomas M. Brocher
U.S. Geological Survey
P.O. Box 94025, Mail Stop 977
Menlo Park, CA 94025
phone: (650) 329-4737
e-mail: brocher@usgs.gov

Robert C. Bucknam
U.S. Geological Survey (Retired)
P.O. Box 25046, Mail Stop 966
Denver, CO 80225-0046
phone: (303) 273-8566
e-mail: bucknam@usgs.gov

Richard L. Dart
U.S. Geological Survey
P.O. Box 25046, Mail Stop 966
Denver, CO 80225-0046
phone: (303) 273-8637
e-mail: dart@usgs.gov

Peter J. Haeussler
U.S. Geological Survey
4200 University Drive
Anchorage, AK 99508
phone: (907) 786-7401
email: pheusler@usgs.gov

Kathleen M. Haller
U.S. Geological Survey
P.O. Box 25046, Mail Stop 966
Denver, CO 80225-0046
phone: (303) 273-8616
e-mail: haller@usgs.gov

David J. Harding
NASA's Goddard Space Flight Center
Geodynamics Branch, Mail Code 921
Greenbelt, MD 20771-0001
phone: (301) 614-6503
e-mail: David.J.Harding@nasa.gov

Samuel Y. Johnson
U.S. Geological Survey
P.O. Box 25046, Mail Stop 966
Denver, CO 80225-0046
phone: (303) 273-8608
e-mail: sjohnson@usgs.gov

Harvey M. Kelsey
Humboldt State University
Department of Geology
Arcata, CA 95521
phone: (707) 826-3991
e-mail: hmkl@axe.humboldt.edu

David J. Lidke
U.S. Geological Survey
P.O. Box 25046, Mail Stop 966
Denver, CO 80225-0046
phone: (303) 273-8541
e-mail: dlidke@usgs.gov

Michael N. Machette
U.S. Geological Survey
P.O. Box 25046, Mail Stop 966
Denver, CO 80225-0046
phone: (303) 273-8612
e-mail: machette@usgs.gov

Patricia A. McCrory
U.S. Geological Survey
P.O. Box 94025, Mail Stop 977
Menlo Park, CA 94025-3561
phone: (650) 329-5677
e-mail: pmccrory@usgs.gov

Alan R. Nelson
U.S. Geological Survey
P.O. Box 25046, Mail Stop 966
Denver, CO 80225-0046
phone: (303) 273-8592
e-mail: anelson@usgs.gov

Stephen F. Personius
U.S. Geological Survey
P.O. Box 25046, Mail Stop 966
Denver, CO 80225-0046
phone: (303) 273-8611
e-mail: personius@usgs.gov

Thomas L. Pratt
U.S. Geological Survey
University of Washington, Box 357940
Seattle, WA 98195
phone: (206) 543-7358
e-mail: tpratt@usgs.gov

Brian L. Sherrod
U.S. Geological Survey
University of Washington, Box 351310
Seattle, WA 98195
phone: (253) 653-8358
e-mail: bsherrod@usgs.gov

Timothy J. Walsh
Washington Division of Geology and Earth
Resources, Department of Natural Resources
P.O. Box 47007
Olympia, WA 98504-7007
phone: (360) 902-1432
e-mail: tim.walsh@wadnr.gov

Ray E. Wells
U.S. Geological Survey
P.O. Box 94025, Mail Stop 975
Menlo Park, CA 94025
phone: (650) 329-4933
e-mail: rwells@usgs.gov

Michael W. West
Michael W. West and Associates, Inc.
6970 S. Holly Circle, Suite 206
Centennial, CO 80112-1066
phone: (720) 529-5300
e-mail: mwestassoc@m-west-assoc.com

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