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San Andreas fault zone, Santa Cruz Mountains section (Class A) No. 1d

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Compiled in cooperation with the California Geological Survey

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Synopsis	**General:** The 1,100-km-long San Andreas fault zone is the principal element of the San Andreas fault system, a network of faults with predominantly dextral strike-slip displacement that collectively accommodates the majority of relative N-S motion between the North American and Pacific plates. Major elements of the San Andreas fault system include the Bartlett Springs [29], Maacama [30], Rodgers Creek [32], Green Valley [37], Calaveras [54], Hayward [55], San Gregorio [60], San Jacinto [125], Elsinore [126], and Imperial [132] fault zones. In this compilation, the San Andreas fault zone is considered to be the

Holocene and historically active dextral strike-slip fault that extends along most of coastal California from its complex junction with the Mendocino fault zone [18] on the north, southeast to the northern Transverse Range and inland to the Salton Sea, where a well-defined zone of seismicity (the Brawley Seismic Zone [124]) transfers slip to the Imperial fault [132] along a right-releasing step. Two major surface-rupturing earthquakes have occurred in historic time: the 1857 Fort Tejon (Sieh, 1978 #5775) and 1906 San Francisco (Lawson, 1908 #4969) earthquakes. Additional historic surface rupturing earthquakes include the unnamed 1812 earthquake along the Mojave section [1h] (Jacoby and others, 1988 #4962; Sieh and others, 1989 #5779; Fumal and others, 2002 #5726) and the northern part of the San Bernardino Mountains section [1i] (Weldon and Sieh, 1985 #5806; Jacoby and others, 1987 #4961; 1988 #4962), and a large earthquake in the San Francisco Bay area that occurred in 1838 that was probably on the Peninsula section [1c] of the San Andreas fault (Toppozada and Borchardt, 1998 #5493; Bakun, 1999 #4790). Historic fault creep at rates as high as 32 mm/yr characterizes the 132-km-long Creeping section [1e] in central California (Burford and Harsh, 1980 #4806). The creep rate gradually tapers off to 0 mm/yr at the northwestern and southeastern ends of this section. The northern and southern ends of the Creeping section [1e] are transitional to the surface-rupture termination points of the 1906 earthquake to the north and 1857 earthquake to the south. Creep at rates as high as 4 mm/yr also has been measured on the Coachella section [1j] (Sieh and Williams, 1990 #5780). The San Andreas fault zone is the most extensively studied fault in California, and perhaps in the world. The fault zone first gained international scientific attention immediately following the great 1906 San Francisco earthquake. Lawson's 1908 report summarizing the investigation of the 1906 earthquake contained the first integrated description of the San Andreas fault, which was recognized as extending from Point Delgada in the north to Whitewater Canyon southeast of San Bernardino in the south, and formed the underlying basis for our modern studies of paleoseismology and earthquake geology (Prentice, 1999 #5755). More than 5,000 articles, maps, and publications describing various aspects of the San Andreas fault that have been produced since Lawson's pioneering work. In addition, there are about 1,000 site-specific fault rupture investigation reports (and maps) filed with the California Geological Survey in compliance with the Alquist-Priolo Earthquake Fault Zoning Act (Hart and Bryant, 1997 #4856). For this compilation, 51 detailed paleoseismic study sites along the fault zone are summarized. The fastest, generally accepted Holocene slip rate for the San Andreas fault is along the Cholame-Carrizo section [1g], which lies in the medial portion of the 1,100-km-long fault zone. Here, Sieh and Jahns (1984 #5778) reported a preferred late Holocene dextral slip rate of 33.9±2.9 mm/yr. In and south of the San Francisco Bay area, a significant portion of dextral slip is partitioned onto several faults of the San Andreas fault system, including the San Gregorio [60] on the west, and the Calaveras [54] and Hayward [55] faults on the east. Hall and others (1999 #4954) reported a late Holocene slip rate of 17±4 mm/yr for the Peninsula section [1c]. North of the Golden Gate, dextral slip from the San Gregorio fault zone [60] may be transferred to the North Coast section [1b] along a right-releasing step. Reported late Holocene slip rates for the North Coast section [1b] range from a minimum value of 16–18 mm/yr reported by Noller and others (1996 #5748) to a maximum value of 25.5±2.5 mm/yr reported by Prentice (1989 #5754). To the south, the San Andreas fault zone is delineated by an extremely complex zone of dextral strike-slip, reverse-oblique, and thrust faults in the southeastern Transverse Ranges. Fault nomenclature in the San Gorgonio Pass area is complex and different workers have assigned faults different names. West-northwest of San Gorgonio Pass Dibblee (1964 #1340; 1968 #4817; 1982 #4841) termed the principal active strand of the San Andreas fault located along the foot of the San Bernardino Mountains the South Branch San Andreas fault, which is referred to as the San Andreas fault by Allen (1957 #4787) and San Bernardino strand San Andreas fault by Matti and others (1992 #5735). For this compilation, this strand will be referred to as the San Andreas fault (South Branch). A fault that strikes sub-parallel located to the north was called the North Branch San Andreas fault by Dibblee (1964 #1340; 1968 #4817) and is referred to as the Mill Creek fault by Allen (1957 #4787), Matti and others (1992 #5735), and Jennings (1994 #2878). This strand will be referred to as the Mill Creek fault in this compilation. East-southeast of San Gorgonio Pass two principal dextral strike-slip faults comprise the Holocene active San Andreas fault zone. The southern trace has been referred to as the South Branch San Andreas fault by Dibblee (1967 #1345; 1981 #4840) and Jennings (1994 #2878); Matti and others (1992 #5735) refer to this trace as the Coachella Valley segment, Banning fault. This branch will be referred to as the South Branch San Andreas fault (Banning strand) in this compilation. The northern trace is referred to as the North Branch San Andreas fault by Dibblee (1967 #1345; 1981 #4840) and Jennings (1994 #2878); Mission Creek fault by Allen (1957 #4787); Matti and others (1992 #5735) named this trace the Coachella Valley segment, San Andreas fault and will be referred to as the North Branch San Andreas fault (Coachella strand) in this compilation. Refer to Matti and others (1992 #5735) for a detailed discussion of San Andreas fault nomenclature for the Mojave [1h], San Bernardino [1i], and Coachella [1j] sections. Weldon and Sieh (1985 #5806) reported a Holocene slip rate of 24±4 mm/yr at the northern end of the San Bernardino Mountains section [1i]. Harden and Matti (1989 #4955) reported a preferred Holocene slip rate of 14 mm/yr to 25 mm/yr near Yucaipa along the San Andreas fault (South Branch). Keller and others (1982 #4964) reported a preferred late Quaternary slip rate of 23 mm/yr to 35 mm/yr for the Coachella section [1j] near Biskra Palms. Surface-exposure age constraints (10Be-26Al) of the offset alluvial fan complex at Biskra Palms yields a better constrained late Quaternary dextral slip rate of 23.3±3.5 mm/yr (van der Woerd and others, 2001 #5800). Several average values of recurrence have been reported for the fault zone; in general they range from a little more than 100 to as much as 450 yr. The North Coast section [1b] ranges from 180–260 yr (Niemi and Hall, 1992 #5747) to 200≠400 yr for the past 2 k.y. (Prentice, 1989 #5754). The Santa Cruz Mountains section [1d] is 247-266 yr (Schwartz and others, 1998 #5771) and the Cholame-Carrizo section [1g] is 160–450 yr (Sieh and Jahns, 1984 #5778; Grant and Sieh, 1994 #4950; Sims, 1994 #5787; Stone and others, 2002 #5792). Recurrence intervals for the Mojave section [1h] are well-constrained based on paleoseismic studies by Sieh and others (1989 #5779), Biasi and others (2002 #5724) and Fumal and others (1993 #624; 2002 #5725). Sieh and others (1989 #5779) reported an average recurrence interval of 132 yr for the time interval AD 734 to 1857 at Pallett Creek, whereas Biasi and others (2002 #5724) refined the average recurrence interval at 135 yr. Fumal and others (2002 #5725) reported an average recurrence interval of 105 yr for the past 500 yr at Wrightwood. An average recurrence interval of 150–275 yr has been reported for the northern San Bernardino Mountains section by Weldon and Sieh (1985 #5806), Seitz and Weldon (1994 #5772), and Yule and others (2001 #4948). The Coachella section [1j] averages large earthquakes about 207–233 yr based on Sieh (1986 #5777).

Sections: This fault has 10 sections. From north to south they are the Shelter Cove [1a], North Coast [1b], Peninsula [1c], Santa

	Cruz Mountains [1d], Creeping [1e], Parkfield [1f], Cholame-Carrizo [1g], Mojave [1h], San Bernardino Mountains [1i], and Coachella [1j] sections. Different behavior patterns along different parts of the San Andreas fault where first noticed when Steinbrugge and Zacher (1960 #5791) documented creep along the fault in central California. Since that time, other workers have proposed various segmentation models for the San Andreas fault including five segments by Allen (1968 #4788), eight segments by Wallace (1970 #1423), 12 segments by Sykes and Nishenko (1984 #5794), Petersen and others (1996 #4860), the Working Group on California Earthquake Probabilities (1988 #5494; 1995 #4945; 1999 #4946), and the Working Group on Northern California Earthquake Probabilities (1996 #1216). Some segment boundaries are well documented or constrained for the San Andreas fault zone, whereas others are not. For this compilation, boundaries generally are similar to those described in models adopted by the Working Group on California Earthquake Probabilities (1988 #5494; 1990 #549; 1995 #4945; 1999 #4946), the Working Group on Northern California Earthquake Probabilities (1996 #1216), and Petersen and others (1996 #4860).
Name comments	**General:** Traces of the San Andreas fault were first mapped in northern California by Lawson (1893 #4967) and were first named the San Andreas rift by Lawson (1895 #4968) after the type locality of the fault in the San Andreas Valley (San Mateo County, California). North of San Francisco, Anderson (1899 #4789) mapped traces of the fault on the Point Reyes Peninsula, but did not name the fault. Schuyler (1896–1897 #5769) described parts of the fault zone in southern California for a 200-mi (about 320-km) length through Kern, Los Angeles, and San Bernardino Counties and referred to the fault not as the San Andreas but as the "great earthquake crack", referring to surface fault ruptures associated with the 1857 Fort Tejon earthquake. The significance and extent of the San Andreas fault was not recognized until after the 1906 San Francisco earthquake. J.C. Branner and S. Tabor proposed the name Portola-Tomales for the fault zone, but A.C. Lawson (1908 #4969) preferred the term "San Andreas fault" (Hill, 1981 #4958). For this compilation, we use San Andreas fault zone owing to the complex nature and multiple strands (or faults) that comprise the structure. **Section:** The Santa Cruz Mountains section extends from the vicinity of Black Mountain in the northern Santa Cruz Mountains southeast to just south of San Juan Bautista. The northern

	boundary is marked by an approximately 1-km-wide, left-compressional bend near Black Mountain. The southern boundary with the Creeping section [1e] is taken as the approximate southern termination of surface fault rupture associated with the 1906 San Francisco earthquake (Lawson, 1908 #4969; Thatcher and others, 1997 #5795). **Fault ID:** Refers to Jennings (1994 #2878) numbers 87 (San Andreas fault (SAF) Shelter Cove), 116 (SAF splays), 119 (SAF Fort Ross to Manchester), 145 (SAF offshore), 147 (SAF offshore Bolinas), 162 (SAF boundary faults), 194 (SAF San Francisco to Watsonville), 217 (SAF 1989 ground fractures), 234 (SAF San Juan Bautista to Priest Valley), 240 (SAF historic creep), 278 (SAF Priest Valley to Cuyama), 311 (SAF Cuyama to Palmdale), 358 (SAF Palmdale to Cajon Canyon), 360 (SAF 1812 rupture), 427 (Mill Creek), 427A (SAF Cajon Canyon to Burro Flats), 452 (SAF South Branch), 453 (SAF North Branch), 472 (SAF Indio to Salton Sea), 477 (SAF Bombay Beach and vicinity), 452 (SAF South Branch), 449 (Banning fault western part), and 450 (Mission Creek fault), and numbers A1 (SAF 1906 rupture), A2 (SAF Peninsula), A3 (SAF Santa Cruz Mountains), and A7 (SAF creeping section) of the Working Group on Northern California Earthquake potential (1996 #1216).
County(s) and State(s)	SAN BENITO COUNTY, CALIFORNIA SANTA CLARA COUNTY, CALIFORNIA SANTA CRUZ COUNTY, CALIFORNIA
Physiographic province(s)	PACIFIC BORDER
Reliability of location	Good Compiled at 1:24,000 scale. *Comments:* Location based on digital revisions to Jennings (1994 #2878) 1:750,000-scale map using original mapping by Sarna-Wojcicki and others (1975 #1247), Brabb and Dibblee (1979 #4799), Dibblee and Brabb (1978 #4844), Dibblee and others (1978 #4843), Bryant (1991 #4804), Bryant and others (1981 #4805), Dibblee (1980 #4838) at 1:24,000 scale and mapping by Rogers and Armstrong (1973 #5814) at 1:12,000 scale.
Geologic setting	The San Andreas fault zone is a major dextral strike-slip fault zone that extends for about 1,100 km along the western side of California. It is near the coast in northern California, but stays

	entirely inland to the south of San Francisco, extending all the way to the northern Gulf of California in Mexico. The San Andreas fault zone is the principal element of a network of dextral strike-slip faults that constitute the San Andreas fault system that collectively accommodates the majority of relative N-S motion between the Pacific and North American plates (Wallace, 1990 #5804). Wilson (1965 #4947) first proposed that the San Andreas fault was a transform fault connecting two spreading oceanic ridges between the Pacific and North American plates. The San Andreas fault zone extends from the Salton Trough near Bombay Beach northwest to its complex junction with the Mendocino fault zone [18] near Punta Gorda. At the southern end of the fault zone near Bombay Beach, dextral slip is transferred to the Imperial fault [132] along a right-releasing step-over delineated by a zone of seismicity referred to as the Brawley Seismic Zone [124]. The San Andreas fault traverses the length of the Coast Ranges geomorphic subprovince and forms the boundary between the Transverse Range and Mojave Desert geomorphic subprovinces as well as the boundary between the Salton Trough and Mojave Desert geomorphic subprovinces. Noble (1926 #1592) was the first to suggest a large amount of dextral slip (38 km) on the San Andreas fault. Hill and Dibblee (1953 #923) postulated that as much as 560 km of dextral slip has occurred on the basis of proposed correlation of Mesozoic basement rocks. Post-early Miocene cumulative dextral slip is approximately 315 km, based on correlation of the Neenach Volcanic Formation (22.5–24.1 Ma minimum K-Ar age reported in Sims, 1993 #5786) on the east side of the fault zone with early Miocene Pinnacles Formation (24.2±0.5 Ma average K-Ar age reported in Sims, 1993 #5786) on the west side of the fault (Matthews, 1976 #931). Stanley (1987 #5790) reported 325–330 km of post late Oligocene dextral slip and 320–325 km of post-early Miocene dextral slip. Further discussions of the displacement history the San Andreas fault zone are included in Powell (1993 #5753), Weldon and others (1993 #5807), and Matti and Morton (1993 #5737).
Length (km)	This section is 75 km of a total fault length of 1082 km.
Average strike	N49°W
Sense of movement	Right lateral *Comments:* Well-defined geomorphic expression of dextral strike-slip faulting (Sarna-Wojcicki and others, 1975 #1247; Bryant and

	others, 1981 #4805; Bryant, 1991 #4804), dextral displacement associated with 1906 San Francisco earthquake (Lawson, 1908 #4969), and geodetically determined dextral slip (Thatcher and others, 1997 #5795).
Dip	80° E. *Comments:* Vertical dip based on linear geomorphic expression of fault; vertical to near vertical fault zone expressed in trench exposures by Schwartz and others (1998 #5771) and Tom Fumal (personal commun., 1999). Well-defined seismicity suggests 80° E. dip at depth (Hill and others, 1990 #4957).
Paleoseismology studies	Three studies sites have been investigated along the Santa Cruz Mountains section. Grizzly Flat site (1-35). Schwartz and others (1998 #5771) excavated three fault normal trenches across the 1906 surface fault rupture trace at the Grizzly Flat site in the southern Santa Cruz Mountains. Faulted late Holocene alluvial and colluvial deposits exposed in the trenches allowed the identification of the most recent earthquake and estimate of a preliminary recurrence interval. Mill Canyon site (1-39) and Arano Flat site (1-14). Investigations by Fumal and others (1999 #4846) included two paleoseismic sites near Watsonville—the Mill Canyon site and Arano Flat site. At Arano Flat 11 trenches were excavated and at Mill Canyon seven trenches were excavated. Faulted late Holocene and historical deposits were exposed, allowing identification of paleoearthquakes and estimation of slip per event and a preliminary recurrence interval.
Geomorphic expression	The Santa Cruz Mountains section is delineated by geomorphic features characteristic of Holocene dextral offset such as dextrally deflected and offset drainages, linear drainages, sidehill benches, closed depressions, aligned benches, linear scarps, linear troughs, aligned saddles, and linear vegetation contrasts (Sarna-Wojcicki and others, 1975 #1247; Bryant and others, 1981 #4805; Bryant, 1991 #4804). Surface traces of the fault locally are complex and distributive and/or concealed by massive landslide deposits (Sarna-Wojcicki and others, 1975 #1247; Bryant, 1991 #4804).

Age of faulted surficial deposits	Faulted late Holocene and historic alluvial and colluvial deposits exposed in trenches at Grizzly Flat site range in age from 3198±110 cal yrs BP to 155±48 cal yrs BP (dendro-corrected radiocarbon ages in Schwartz and others, 1998 #5771). Fumal and others (1999 #4846) reported faulted late Holocene and historic fluvial and debris-flow deposits at the Mill Creek and Arano Flat sites. The age of faulted deposits are controlled by AMS 14C dates on more than 130 samples.
Historic earthquake	San Francisco earthquake 1906
Most recent prehistoric deformation	latest Quaternary (<15 ka) *Comments:* The most recent event is the 1906 San Francisco earthquake. The most recent paleoearthquake along the Santa Cruz Mountains section may have occurred in the mid 1600s, based on interpretation of trench excavations by Schwartz and others (1998 #5771) at the Grizzly Flat site. It is possible that surface fault rupture associated with the 1838 earthquake may have extended as far south as the Grizzly Flat site, but evidence of this earthquake was not recognized in the trenches (Schwartz and others, 1998 #5771). Three large earthquakes have occurred at the Mill Canyon site since AD 1670. Radiocarbon dates from Arano Flat site indicate that the most recent paleoearthquake occurred between AD 1750 and AD 1800, but this may be the 1838 earthquake based on the presence of a fissure fill overlain by historic, pre-1906 alluvium at Mill Canyon site. Fumal and others (1999 #4846) point out that further work needs to be completed to better constrain the timing of the most recent paleoevent.
Recurrence interval	133–266 yr (< 900 yr) *Comments:* Schwartz and others (1998 #5771) reported that 247 to 266 yr elapsed between the 1906 earthquake and the most recent paleoevent at Grizzly Flat, which probably occurred in the mid 1600s. However, at Arano Flat and Mill Canyon the elapsed time since 1906 was only 68–150 yr. If the most recent event occurred in 1838, then 133 yr elapsed before the 1906 event. Fumal and others (1999 #4846) identified as many as seven large earthquakes since AD 1100.
Slip-rate category	Greater than 5.0 mm/yr *Comments:* Fumal and others (1999 #4846) reported a preliminary slip rate of about 22 mm/yr based on the observation

	that the axis of a fold developed within a left-step of the fault zone has been dextrally displaced about 11 m since AD 1400.
Date and Compiler(s)	2002 William A. Bryant, California Geological Survey Matthew Lundberg, California Geological Survey
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