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North Frontal thrust system, Western section (Class A) No. 109a

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Synopsis	**General:** The North Frontal thrust system is a major, generally east-west trending fault zone that marks the boundary between the Transverse Ranges and Mojave Desert geomorphic provinces. This fault zone is characterized by a broad, complex zone of discontinuous, generally south-dipping thrust, reverse, and, locally, strike-slip faults with latest Pleistocene to Holocene offset. Geologic and geomorphic mapping includes Vaughn (1922 #5801), Woodford and Harriss (1928 #6726), Gillou (1953 #6730), Richmond (1960 #6728), Hollenbaugh (1968 #6634), Dibblee (1964 #1343; 1967 #6614; 1974 #6605), Sadler (1982 #6619), Meisling (1984 #6606), and Miller (1987 #6617), Bryant (1986 #6611; 1986 #6612), and Spotila (2001 #6622). In this compilation the fault zone is divided into the Western [109a] and the Eastern [109b] sections. The Western section includes the Ord Mountains fault zone, Ocotillo Ridge fold, Sky High Ranch fault,

and White Mountains Thrust. The Eastern section extends eastward from the Helendale fault [110b] and includes the Blackhawk fault zone and other unnamed thrust and reverse faults. There are two detailed study sites along the Western section [109a]. Site 109-1 involved a trench by Meisling (1984 #6606) across the Ocotillo Ridge fold. This trench exposed a monoclinal warp expressed as a 55° north-dipping section of coarse fluvial sand and gravel overlying massive debris-flow deposits. Site 109-2 by Spotila (2001 #6622) exposed Holocene thrust displacement (maximum age of offset 9,710±50 yr BP) along a 23° south-dipping fault. In addition, Spotila measured 16 fault scarp profiles across traces of the Western [109a] and Eastern [109b] sections. There are no detailed studies for the Eastern section [109b]. Slip rates for the North Frontal thrust system are poorly constrained, especially with respect to age of displacement. Clark and others (1984 #2876) reported a long term vertical slip-rate of 0.07–0.14 mm/yr for the Ord Mountains fault zone. Bryant (1986 #6612) estimated the vertical slip rate of reverse and thrust faults along the Western section to be about 0.15–0.3 mm/yr, based on reported 40 m vertical offsets of Qf2 alluvial fan surfaces (Meisling, 1984 #6606). Meisling (1984 #6606) estimated a preferred vertical slip rate of 0.1–0.14 mm/yr for the Ord Mountains fault zone, based on offset late Quaternary alluvial fans and deposits. His maximum vertical slip rate along the Ord Mountains fault zone was 0.7–1.2 mm/yr. Wesnousky (1986 #5305) and Petersen and Wesnousky (1994 #6024) assign similar values based on Meisling (1984 #6606). Meisling (1984 #6606) estimated a preferred dextral slip rate of 1.25 mm/yr (0.34–15 mm/yr) for the Sky High Ranch fault, based on 250–750 m dextral offset Qf2 fanglomerate deposits estimated to be 50–730 ka. No slip rates have been reported for the Eastern section. The geomorphic expression and lower frequency of mapped Holocene displacement suggest that the slip rate for the Eastern section is probably less than slip rates estimated for the Western section. No recurrence interval studies exist for the Western and Eastern sections.

Sections: This fault has 2 sections. There is insufficient data to delineate seismogenic segments. Spotila (2001 #6622) divided the North Frontal thrust system into 3 segments. The Western segment extended north-south along the western flank of the Ord Mountains, then east along the northern front of the San Bernardino Mountains its intersection with the Helendale fault [110b]. Spotila's Central segment extended east from the

	Helendale fault [110b] to its intersection with the Old Woman Springs fault [117]. The Eastern segment extended east to a location about 4 km west of Highway 247. In this compilation the North Frontal thrust system is divided into 2 sections, the Western section west of the Helendale fault, and the Eastern section, which extends eastward to about 4 km west of Highway 247. Spotila (2001 #6622) observed that young-looking traces of the North Frontal thrust system are much more common west of the Helendale fault [110b] than east of the Helendale fault.
Name comments	**General:** The North Frontal thrust system is a complex zone of thrust, reverse, and dextral strike-slip faults that have a complicated mapping and naming history. Mendenhall (1905 #6616) was the first to recognize the steep north-facing escarpment along the northern San Bernardino Mountains. Vaughn (1922 #5801), Woodford and Harriss (1928 #6726), Gillou (1953 #6730), Richmond (1960 #6728), and Hollenbaugh (1968 #6634) all reported evidence of late Cenozoic deformation and faulting of various locations along the northern front of the San Bernardino Mountains. Woodford and Harriss (1928 #6726) mapped the geology in the vicinity of Blackhawk Mountain and named south-dipping thrust faults in bedrock (Santa Fe, Voorhies, and Grapevine thrusts). Shreve (1968 #6620) used these names and collectively termed these bedrock thrusts the Santa Fe thrust zone. Dibblee (1964 #1343; 1967 #6614; 1974 #6605) mapped along the entire range front and presented evidence for late Quaternary uplift in the San Bernardino Mountains (Dibblee, 1974 #6605; 1975 #6678). Dibblee, however, did not name faults along the northern range front. Meisling (1984 #6606) and Meisling and Weldon (1989 #6607) named faults along the northern front of the San Bernardino Mountains the North Frontal fault system, but this system included the Cleghorn [108], Grass Valley [108], Tunnel Ridge [327], Bowen Ranch [326], and Arrastre Canyon Narrows [325] faults. These faults will be considered in separate compilations. Meisling (1984 #6606) further named the individual fault zones within this system, from west to east: Ord Mountains fault zone (includes the Deep Creek fault on the south and Apple Valley Highlands fault on the north); Ocotillo Ridge fold, Sky High Ranch fault, and White Mountains Thrust system. Meisling and Weldon (1989 #6607) termed faults along the northern front of the San Bernardino Mountains, from west to east, the Deep Creek fault zone (along the western flank of the Ord Mountains), the Sky High Ranch fault (a northwest-striking dextral strike-slip fault), and the North Frontal thrusts. Ziony and Yerkes (1985 #5931) called the fault zone the North

	Frontal Fault Zone of San Bernardino Mountains. Bortugno and Spittler (1986 #6602) and Bryant (1986 #6611; 1986 #6612) used the name North Frontal Fault zone for the recently active thrust faults along the north face of the San Bernardino Mountains. Miller (1987 #6617) informally referred to the range-bounding reverse faults as the frontal fault system. He did not name the system. Spotila and Sieh (2000 #6623) termed the range-bounding faults as the North Frontal thrust system. This system included the Ord Mountains fault zone, Ocotillo Ridge fold, Sky High Ranch fault, White Mountain thrust (system), Blackhawk fault, and unnamed thrust and reverse faults east of Blackhawk Mountain. Wesnousky (1986 #5305) may have been the first to name thrust faults east of the Helendale fault [110b] the Black Hawk Spring fault. The name North Frontal thrust system will be used in this compilation. Individual fault names within this fault zone, from west to east, include: Ord Mountains fault zone, Ocotillo Ridge fold, White Mountains Thrust, and Blackhawk fault zone. **Section:** The Western section in this compilation extends from the southern end of the Ord Mountains fault zone about 2 km south of Deep Creek north along the Ord Mountains range front, then eastward expressed as the Ocotillo Ridge fold and east-southeast along the northern front of the San Bernardino Mountains to its complex intersection with the Helendale fault [110b] near Cushenbury Canyon and Highway 18. Spotila (2001 #6622) divided the North Frontal thrust system into 3 segments—his western segment corresponds to the Western section in this compilation. Principal faults in the Western section include: Ord Mountains fault zone, which was further divided into the Deep Creek fault and Apple Valley Highlands faults by Meisling (1984 #6606); Ocotillo Ridge fold; Sky High Ranch fault named by Meisling (1984 #6606); White Mountains Thrust (system) named by Meisling (1984 #6606). **Fault ID:** Includes numbers 405 (Ord Mountains fault) 407 (North Frontal Fault zone), 408 (Sky High Ranch fault) of Jennings (1994 #2878), and number 93 (North Frontal fault zone of San Bernardino Mountains) of Ziony and Yerkes (1985 #5931).
County(s) and State(s)	SAN BERNARDINO COUNTY, CALIFORNIA
Physiographic province(s)	BASIN AND RANGE PACIFIC BORDER

Reliability of location	Good Compiled at 1:48,000 scale. *Comments:* Locations based on digital revisions to Jennings (1994 #2878) using original mapping by Meisling (1984 #6606) and Bryant (1986 #6612) at 1:24,000; mapping by Miller (1987 #6617) is at 1:48,000.
Geologic setting	The North Frontal thrust system is a major range front fault system, located between the Transverse Ranges to the south and Mojave Desert to the north, along which uplift of the northern San Bernardino Mountains has occurred. The 80-km-long fault system consists of a complex zone of generally east-, north-, and northwest-trending thrust, reverse, and strike-slip faults that is locally 2 km wide. Meisling and Weldon (1989 #6607) and Spotila and Sieh (2000 #6623) reported that uplift of a broad plateau consisting of a relict, low-relief granitic erosion surface initiated on the North Frontal thrust system between 1.5–3 Ma. Maximum vertical displacement along the North Frontal thrust system is about 2.9 km near the center of the fault system (Spotila and Sieh, 2000 #6623). Displacement is not equally distributed along the system. Vertical offset drops to zero on the eastern end of the system, but is about 610 m at the western end of the system (Spotila and Sieh, 2000 #6623). Complex intersections with dextral strike-slip faults of the Mojave Desert characterize the eastern extent of the Western section [109a] and Eastern section [109b]. The intersection of the Helendale-South Lockhart fault zone [110] and North Frontal thrust system near Cushenbury Canyon is complex and there are differing interpretations as to whether the Helendale fault [110b] is a through-going dextral strike slip fault or if north-vergent reverse displacement along the North Frontal thrust system is dominant (Dibblee, 1964 #1343; Hollenbaugh, 1968 #6634; Sadler, 1982 #6619; Bryant, 1986 #6611; Miller, 1987 #6617; Meisling and Weldon, 1989 #6607). Miller (1987 #6617) and Bryant (1986 #6611) mapped strands of the North Frontal thrust system as continuous across the strike of the Helendale fault [110b]. Miller (1987 #6617) reported that both the Helendale [110b] and Old Woman Springs [117] faults do not appear to extend into the rocks south of the frontal fault system. Miller stated that offset along the Helendale fault [110b] may continue to the south beneath the San Bernardino Mountains, but displacement is confined to the block beneath the north-vergent thrust faults. Spotila (1999 #6621) suggested that, because no clear crosscutting relationship between the dextral strike-slip

	faults north of the North Frontal thrust system have been mapped, it is likely that both fault systems are active.
Length (km)	This section is 39 km of a total fault length of 67 km.
Average strike	N87°W
Sense of movement	Thrust *Comments:* Thrust displacement is the predominate sense of offset along most strands of the North Frontal thrust system (Dibblee, 1964 #1343; 1974 #6605; Meisling, 1984 #6606; Meisling and Weldon, 1989 #6607; Spotila and Sieh, 2000 #6623), but dips locally are steeper along traces of the Mountains fault zone (45° or greater) and the Sky High Ranch fault generally has a linear strike across moderate to moderately strong relief and is delineated by geomorphic features indicative of dextral strike-slip offset (Meisling, 1984 #6606; Bryant, 1986 #6612).
Dip	30–35° S. *Comments:* Subsurface dip values are not well constrained. Spotila and Sieh (2000 #6623) state that surface dips range from 10–60°, but average subsurface dip may be 30–35° (Meisling, 1984 #6606; Miller, 1987 #6617; Spotila and Sieh, 2000 #6623). A seismic reflection profile by Li and others (1992 #6615) shows that the North Frontal thrust system retains a dip of about 10° in the upper 1 km of crust. The dip direction along the eastern part of the Western section dips to the south, but as the strike changes for the Ord Mountains fault zone from generally east-west to north-south, the fault zone dips to the east.
Paleoseismology studies	Site 109-1 by Meisling (1984 #6606) involved the excavation of one 20-m-long fault normal trench across the north-facing escarpment delineating the Ocotillo Ridge fold. This geomorphic feature has been variously mapped as a north-vergent thrust fault (Miller, 1987 #6617), anticline (Dibblee, 1974 #6605), and monoclinal warp (Meisling, 1984 #6606). Trench exposed 55° north-dipping section of coarse fluvial sand and gravel overlying massive debris-flow deposits. The debris-flow deposits contained carbonate-filled fractures, but no units were reported to be offset. Meisling (1984 #6606) concluded that this indicated a monoclinal warp developed over a fault in basement rocks. However, Bryant (1986 #6612) suggested that a fault in alluvium could exist just

	north of the trench site. Site 109-2 by Spotila (2001 #6622) involved the excavation of one 20-m-long bulldozer trench across a 1.7-m-high scarp on Holocene alluvium at Spotila's Mits 1 site about 3 km west of Cushenbury Canyon. Trench exposure documented Holocene thrust displacement along a 23° south-dipping fault. Spotila also measured 16 fault scarp profiles across traces of the Western [109a] and Eastern [109b] sections.
Geomorphic expression	Traces of the Ord Mountains fault zone are delineated by well defined scarps on late Pleistocene alluvium, vertically offset drainages, and linear tonal contrasts in Holocene alluvium (Bryant, 1986 #6612). Young alluvial fans presumably of late Holocene age are not offset. Traces of the Sky High Ranch fault are delineated by geomorphic features indicative of latest Pleistocene to Holocene dextral offset including linear ridges, ponded alluvium, a shutter ridge, and dextrally offset geomorphic surfaces (Bryant, 1986 #6612). Traces of the White Mountains Thrust north and east of the Sky High Ranch fault generally are well defined and are delineated by sinuous, generally north-facing scarps on late Pleistocene alluvium, ponded alluvium, and tonal lineaments in Holocene alluvium (Bryant, 1986 #6611). Spotila (2001 #6622) identified a 1.7-m-high scarp on Holocene alluvium located between two 5-m-high scarps on late Pleistocene alluvium. The Ocotillo Ridge fold is delineated by a degraded north-facing scarp in mid-Pleistocene Ord River Gravel deposits, faceted spurs, and a subtle tonal lineament in Holocene alluvium (Bryant, 1986 #6612).
Age of faulted surficial deposits	Strands of the Western section offset Paleozoic metasedimentary and Mesozoic crystalline basement rocks over late Quaternary alluvial deposits (Dibblee, 1964 #1343; 1974 #6605; Meisling, 1984 #6606; Miller, 1987 #6617), offset late Pleistocene alluvial fans (Qf2 unit of Meisling, 1984 #6606; age of Qf2 fan surface about 130 ka, based on soil profile development as determined by G. Borchardt in Bryant (1986 #6612). A strand of the White Mountains Thrust offsets alluvial gravels that were dated at 9,710±50 yr BP (site 109-2) (Spotila, 2001 #6622). Younger alluvium at this site is offset an equal amount, but there is no

	minimum age of the displacement (Spotila, 2001 #6622).
Historic earthquake	
Most recent prehistoric deformation	latest Quaternary (<15 ka) *Comments:* Timing of the most recent paleoevent is not well constrained. A strand of the White Mountains Thrust offset alluvial gravels that were dated at 9,710±50 yr BP (Spotila, 2001 #6622). Spotila considered this a maximum age of displacement because younger alluvial deposits are also offset, but no minimum age was determined. Spotila speculated that this displacement could be quite recent because deposition and soil development of the deposits and associated paleosols overlying the 9.7 ka gravel deposit may have required most of this time period.
Recurrence interval	
Slip-rate category	Between 0.2 and 1.0 mm/yr *Comments:* Slip rates are poorly constrained for strands of the Western section. Clark and others (1984 #2876) reported a long term slip-rate (vertical) rate of 0.07–0.14 mm/yr, based on 70 m vertical offset of a 500–1,000 ka alluvial fan surface offset along the Ord Mountains fault zone. Bryant (1986 #6612) estimated the vertical slip rate of reverse and thrust faults along the Western section to be about 0.15–0.3 mm/yr, based on reported 40 m vertical offsets of Qf2 alluvial fan surfaces (Meisling, 1984 #6606). G. Borchardt (in Bryant, 1986 #6612) estimated age of Qf2 alluvial fan surface to be about 130 ka (based on soil-profile development). Meisling (1984 #6606) estimated a preferred vertical slip rate of 0.1–0.14 mm/yr for the Ord Mountains fault zone, based on offset late Quaternary alluvial fans and deposits. His maximum vertical slip rate along the Ord Mountains fault zone was 0.7–1.2 mm/yr. Wesnousky (1986 #5305) and Petersen and Wesnousky (1994 #6024) assign similar values based on Meisling (1984 #6606); he estimated a preferred dextral slip rate of 1.25 mm/yr (0.34–15 mm/yr) for the Sky High Ranch fault, based on 250–750 m dextral offset Qf2 fanglomerate deposits estimated to be 50–730 ka, based on stratigraphic correlation, soil-profile development, and geomorphology. Slip rate assigned by Petersen and others (1996 #4860) for probabilistic seismic hazard assessment for the State of California was 1.0 mm/yr (with

	minimum and maximum assigned slip rates of 0.5 mm/yr and 1.5 mm/yr, respectively).
Date and Compiler(s)	2003 William A. Bryant, California Geological Survey
References	#6 Anderson, A.L., 1959, Geology and mineral resources of the North Fork quadrangle, Lemhi County, Idaho: Idaho Bureau of Mines and Geology Pamphlet 118, 92 p., 10 pls. #6611 Bryant, W.A., 1986, Eastern North Frontal fault zone and related faults, southwestern San Bernardino County: California Division of Mines and Geology Fault Evaluation Report FER-182, microfiche copy in California Division of Mines and Geology Open-File Report 90-14, 20 p., scale 1:24,000. #6612 Bryant, W.A., 1986, Western North Frontal fault zone and related faults, San Bernardino County: California Division of Mines and Geology Fault Evaluation Report FER-186, microfiche copy in California Division of Mines and Geology Open-File Report 90-14, 16 p., scale 1:24,000. #2876 Clark, M.M., Harms, K.H., Lienkaemper, J.J., Harwood, D.S., Lajoie, K.R., Matti, J.C., Perkins, J.A., Rymer, M.J., Sarna-Wojcicki, A.M., Sharp, R.V., Sims, J.D., Tinsley, J.C., III, and Ziony, J.I., 1984, Preliminary slip rate table and map of late Quaternary faults of California: U.S. Geological Survey Open-File Report 84-106, 12 p., 5 plates, scale 1:1,000,000. #1343 Dibblee, T.W., Jr., 1964, Geologic map of the Lucerne Valley quadrangle San Bernardino County, California: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-426, 6 p. pamphlet, 1 sheet, scale 1:62,500. #6614 Dibblee, T.W., Jr., 1967, Geologic map of the Old Woman Springs quadrangle, San Bernardino County, California: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-518, scale 1:62,500. #6605 Dibblee, T.W., Jr., 1974, Geologic map of the Lake Arrowhead quadrangle, San Bernardino County, California: U.S. Geological Survey Open-File Report 73-56, scale 1:62,500. #6678 Dibblee, T.W., Jr., 1975, Late Quaternary uplift of the San Bernardino Mountains on the San Andreas fault in southern

	California: California Division of Mines and Geology Special Report 118, p. 127-135. #6730 Gillou, R.B., 1953, Geology of the Johnson Grade area, San Bernardino County, California: California Division of Mines Special Report 31, 189 p., 1 pl., scale 1:24,000. #6634 Hollenbaugh, K.M., 1968, Geology of a portion of the north flank of the San Bernardino Mountains, California: University of Idaho, Ph.D. thesis, 109 p., 1 pl., scale l:12,000.