The San Andreas and Walker Lane Fault Systems, Western North America: Transpression, Transtension, Cumulative Slip and the Structural Evolution of a Major Transform Plate Boundary

Steven G. Wesnousky
Center for Neotectonic Studies
University of Nevada, Reno, 89557

Abstract

Relative right-lateral Pacific-North American transform motion across the western U.S. is largely taken up by the San Andreas and Walker Lane fault systems. Cumulative lateral displacement on active strands of the San Andreas system is 3 to 4 or more times greater than across faults of the Walker Lane. The San Andreas system is transpressional while the Walker Lane system is transtensional. The relatively more complex, discontinuous and broader system of faults composing the Walker Lane system is attributed to lower slip and an attendant extensional component of motion. Greater slip accompanied by a small component of contraction has yielded the simpler, more continuous and generally throughgoing set of faults that comprise the San Andreas system. In this regard, the San Andreas is at a more mature stage of structural development than the Walker Lane. Despite differences in gross patterns of faulting, the systems also share similarities in deformation style. Slip along each is locally accommodated by clockwise rotation of crustal blocks, and oblique components of slip are commonly partitioned into subparallel strike-slip and dip-slip faults.

Introduction

Pacific-North American relative plate motion is distributed on faults across the western United States **(Figure 1)** (eg., Bennett et al., 2003; Minster and Jordan, 1987). Fault displacement along the northwest-striking San Andreas system takes up the major portion of motion. Most of the remaining transform motion occurs on a similarly trending zone of faults that strikes through the Mojave Desert and bounds the east flank of the Sierra Nevada (Bennett et al., 2003; Dixon et al., 1995; Dokka and Travis, 1990b; Sauber et al., 1986; Thatcher et al., 1999). The zone of faults, all or in part, has been previously referred to as the Walker Lane (Locke et al., 1940), the Walker Line (Billingsley and Locke, 1941), the Walker Belt (Stewart, 1980), the Walker Lane Belt (Carr, 1984), and the Eastern California Shear Zone (Dokka and Travis, 1990b). The earliest accounts of strike-slip faulting east of the Sierra Nevada include Gianella and Callaghan's (1934) description of the 1932 Cedar Mountain earthquake and the mapping of Ferguson and Muller (1949) and Nielsen (1965). I use the terms Walker Lane and Eastern California Shear Zone as shown in **Figure 2** to group and label faults for the following discussion. The San Andreas and Walker Lane fault systems accommodate primarily right-lateral strike-slip parallel to the plate boundary but display distinctly different patterns of faulting. The San Andreas system is composed of relatively smooth, curvilinear, and anastomosing fault traces. The Walker Lane is marked by a generally broader and discontinuous set of strike-slip faults. I first consider observations bearing on both the history of slip and geodetic constraints on the relative motion across each of the fault systems. The observations are the basis to then suggest that marked differences in the style of deformation observed along the two fault systems provides a picture of two major strike-slip systems at a different stage of structural evolution, and that the Walker Lane is a zone of Transtension while the San Andreas is one of Transpression. I also point to deformation characteristics that are shared or universal to both fault systems.

History of Slip

Overview

Deformation distributed across the western United States is attributed primarily to right-lateral transform motion that links plate boundary triple junctions near Cape Mendocino and the Gulf of California (eg., Atwater, 1970, 1989; Bennett et al., 2003). Interpretation of seafloor magnetic lineations indicates approximately 1,100 to 1,500 km of transform motion since inception of the transform ~28-30 Ma (e.g., Stock and Molnar, 1988). A major portion of the plate motion has been taken up along faults of the San Andreas system. The remainder has been taken up by a broad zone of shear east of the San Andreas system which encompasses the Walker Lane and also transform faulting offshore California (Atwater, 1989; Beck, 1986; Garfunkel, 1973; Howell, 1976). Only about one-half to one-third of the estimated total transform motion is attributed to displacement on currently active strands of the San Andreas and Walker Lane fault systems (Powell et al., 1993).

San Andreas

Measures of cumulative right-slip of basement terrain range from about 300 km to 450 km along the southern and northern reaches of the San Andreas fault system, respectively (e.g., Dillon and Ehlig, 1993; James et al., 1993). Most of that displacement has occurred along the San Andreas fault proper. Lesser, albeit significant, amounts are reported for a few of the subsidiary strands as well. Right-slip offset across the San Jacinto fault is ~25 km (Sharp, 1967). Estimates of total right-slip along the Whittier-Elsinore fault vary from about 10 to 40 km (Lamar, 1961; Lamar and Rockwell, 1986; Mueller, 1984; Sage, 1973; Weber, 1977). Total right-lateral displacement estimates along the Newport-Inglewood fault range from <1 km to a maximum of 10 km (Barrows, 1974). Estimates of cumulative offset along secondary strands of the northern San Andreas fault system are apparently limited to a single estimate of 24 km right-slip along the Calaveras fault zone (Kintzer et al., 1977).

Walker Lane

The Eastern California Shear Zone in the Mojave Desert is composed of a set of subparallel northwest striking fault strands **(Figures 1 and 2)**. Each shows high angle dip, right slip, and anastomosing and en echelon segments. Dokka *(1983)* and Dokka and Travis *(1990a)* report right lateral offset of Miocene terrain across the zone of 65 km to 80 km.

The Southern Walker Lane extends northward from the Garlock fault and includes the northwest-striking Owens Valley fault, the Panamint Valley-Hunter Mountain-Saline Valley fault system, and the Death Valley-Furnace Creek-Fish Lake Valley fault system. Estimates of total right-slip on the Furnace Creek-Fish Lake Valley fault zone range from about 40 to 100 km based on offsets of various stratigraphic and geochemical markers and isopach trends (Stewart, 1988). Reheis and Sawyer (1997) favor a value of 40-50 km arising from McGee's (1968) obnservaton of an offset Jurassic quartz monzonite in northern Death

Valley. Paleozoic rocks are right-laterally offset 16-19 km along the State Line fault to the east (Stewart, 1988). Right-lateral displacement on the Hunter Mountain fault is on the order of 8 to 10 km (Burchfiel et al., 1987). Net right slip on the Owens Valley fault system has been considered to be no more than a few kilometers (Moore and Hopson, 1961; Ross, 1962) though Beanland and Clark (1994) argue that 10 to 20 km of right slip is permissive. Thus, cumulative net right-slip across the region is no more than ~150km and likely closer to 75 to 85 km.

The Central Walker Lane includes faults of the Excelsior-Coaldale and the Walker Lake Blocks originally defined by Stewart (1988). Faults of the *Excelsior-Coaldale Block* strike east and record late Quaternary displacement (dePolo, 1993; Oldow et al., 1994). The east striking faults of the Excelsior-Coaldale Block are left-lateral and form a right step between northwest-striking strike-slip faults to the south and north, respectively. Offset Tertiary tuffs and lavas and older granites and volcaniclastic rocks are interpreted to indicate that the northwest-striking strike-slip faults of the *Walker Lane Block* have taken up 48-60 km of right-lateral strike-slip (Ekren and Byers, 1984; Ekren et al., 1980).

Evidence bearing on the history of slip to the north within the Northern Walker Lane and Northern California Shear Zone is minimal to absent. The Northern Walker Lane includes the Carson and Pyramid Lake Blocks of Stewart (1988). Similar to the region of the Excelsior-Coaldale Block, the Carson Block is characterized by zones of easterly-trending left-lateral faults and lineaments (Rogers, 1975; Stewart, 1988). Paleomagnetic studies of Miocene basalts in the Carson Block suggest that left-lateral displacements have been accompanied by 37° to 51° of clockwise vertical-axis rotation since 9-13 Ma (Cashman and Fontaine, 2000). The Pyramid Lake Block is distinguished by a left-stepping set of northwest-trending active right-lateral strike-slip faults. Cumulative offset measurement is limited to the conjecture of Bonham (1969) and recent work of Faulds (2003) that paleovalleys and Cenozoic tuffs are displaced right-laterally about 25-32km across the zone (Stewart, 1988). I am aware of no estimates of cumulative slip across the Northern California Shear Zone.

Plate Tectonic and Geodetic Considerations

Analysis of GPS and plate kinematic data by DeMets and Dixon (1999) places the pole of Pacific-North American plate motion at 50.5°N, 248.2°E with angular velocity of 0.776My^{-1}. The Pacific-North American plate vector derived from the pole is 50 mm/yr at N50°E evaluated 37°N latitude and 121.75° longitude along the central San Andreas fault **(Figure 3).** Bennett et al.'s (2003) recent study provides the most complete picture of how the displacement field is distributed across the western United States. They and Dixon et al. (2000) conclude that the interior region of the Sierra Nevada is acceptably described as a rigid microblock that translates 12 mm/yr oriented N47°W with respect to stable North America. Bennet et al. (2003) further conclude that the 12 mm/yr Sierra-Nevada vector may be divided into two components. The first of these, primarily reflecting extension across the Eastern Great Basin, is 2.8mm/yr at N84°W. The second includes deformation localized within the Walker Lane and western Great Basin and is 9.3mm/yr at N40°W. When decomposing this latter vector into components parallel and perpendicular to the average N30°W trend of the Walker Lane, the result shows a small component of extension oriented perpendicular to the main trend of the Walker Lane **(Figure 3, lower)**, a result also inherent in the recent discussion of Unruh (2003). The difference vector between the Pacific-North American and Sierra-Nevada vectors may be similarly decomposed into San Andreas fault parallel and perpendicular components. The decomposition shows fault parallel motion of 37mm/yr is accompanied by a small component of fault perpendicular shortening (**Figure 3, upper**). In sum, observations indicate the primarily strike-slip fault systems of the Walker Lane and San Andreas are transtensional and transpressional in character, respectively.

Discussion

The general pattern of faulting along the San Andreas fault system is dominated by the relatively smooth and continuous trace of the San Andreas fault. Other subsidiary strike-slip strands such as the San Jacinto and Hayward-Maacama fault systems are essentially interconnected, branching off at small angles to the San Andreas fault. In contrast, there exists no single throughgoing strand along the Walker Lane. Northwest trending strike-slip faults that define the shear zone are discontinuous and interrupted by zones of east trending left-lateral faults. Faults comprising the Walker Lane define a broader and more diffuse pattern than the San Andreas system. Laboratory studies show that strike-slip fault systems are characterized by a zone of discrete fault segments during initial stages of development which ultimately coalesce to take up displacement along a principal and throughgoing fault (eg., Wilcox et al., 1973). As well, prior field observations have shown that individual strike-slip faults show a simplification of fault trace with the accumulation of slip (Stirling et al., 1996; Wesnousky, 1988). The preceding review indicates the Walker Lane and Eastern California Shear Zone have taken up significantly less of the Pacific – North American plate motion than has the San Andreas system. I suggest here that the more complex, diffuse, and discontinuous nature of the fault systems defining Walker Lane and Eastern California Shear Zone is in large part due to differences in cumulative slip registered across the zones. Another factor that may also play a role in the greater complexity of the Walker Lane fault system is the attendant component of extension. The pattern of faulting observed to the west in the Basin and Range suggests a tendency for continental extension to diffuse over broad areas. The component of extension transverse to the Walker Lane may also work against the coalescence and simplification of strike-slip deformation with continued offset.

The small component of motion perpendicular to the main strike-slip faults of the San Andreas and Walker Lane is taken up on subparallel dip-slip faults. The phenomenon was first recognized by Fitch (1972) along major subduction zones and has been discussed in detail along the San Andreas and western Basin and Range (Wesnousky and Jones, 1994). In this case, the components of slip transverse to the main trend of strike-slip structures is taken up by thrust faulting along the San Andreas and normal faulting within the Walker Lane **(Figure 4)**. An example of this behavior along the San Andreas system is the occurrence of the 1980 M6.7 Coalinga thrust and associated folds which strike parallel to the adjacent central San Andreas fault (Jones and Wesnousky, 1992). In like manner, the strike-slip trace of the 1872 M~7.9 Owens Valley earthquake runs parallel to the adjacent Sierra Nevada rangefront normal fault (Wesnousky and Jones, 1994). Hence, the partitioning of slip in this manner is shared by both fault systems.

The San Andreas fault in southern California strikes more easterly than sections to the north and south which more closely parallel the Pacific-North America plate motion vector (**Figure 5**). A large right-step in the traces of major strike-slip faults of the Walker Lane occurs between the Gabbs Valley Range and Wassuk Mountains (**Figure 5**). The northwest trending strike-slip faults strike subparallel to the relative motion vector between the Sierra Nevada and Central Basin and Range. Though the sense of slip or bend differs in each area, the geometries require that the northwest-directed shear in each region be taken up by structures oblique to the main trend of each fault system. Prominent to both regions are east-trending left-lateral strike-slip faults. Crustal blocks within southern California bounded by east-trending left-lateral faults have undergone 35° to 60° of clockwise rotation during the last 10 Ma (Luyendyk et al., 1980), and the rotation remains active today (Jackson and Molnar, 1990). Structural and physiographic observation indicates that the blocks bounded by east-striking left-lateral faults within the Walker Lane step are similarly undergoing clockwise rotation (**Figure 5:** Wesnousky, 2004). The accommodation of right-lateral shear by clockwise vertical axis rotation of crustal blocks is a shared feature of these zones of transtensional and transpressional strike-slip. The Walker Lane fault pattern within the area of **Figure 5** may be analogous to an earlier stage in the structural development of the San Andreas system before sufficient slip accumulated to yield the now throughgoing San Andreas fault.

Conclusion

Right-lateral transform motion due to Pacific-North America relative plate motion is taken up in majority along the San Andreas and Walker Lane fault systems. Cumulative lateral displacement on active strands of the San Andreas system is 3 to 4 or more times greater than recorded on faults of the Walker Lane system. Additionally, the Walker Lane fault system is transtensional and the San Andreas fault system transpressional. The lower cumulative slip and component of extension across the Walker Lane is manifested in a fault system that is more complex and discontinuous than defined by the San Andreas system. In this regard, the San Andreas may be viewed as a more structurally mature strike-slip fault system. Withstanding the difference in fault patterns, the systems share similar behaviors. Regions of fault bends and steps are characterized by east striking left-slip faults bounding crustal blocks which undergo clockwise rotation. The oblique component of slip along each is also locally partitioned between subparallel strike-slip and dip-slip fault.

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Figure Captions

Figure 1. Generalized fault map of western United States. Pacific-North American relative plate motion vector (50mm/yr @ N50°W) from Demets and Dixon (1999). The majority of transform motion is taken up within the Walker Lane, Eastern California Shear Zone (ECSZ), and along the San Andreas fault system. Areas outlined by boxes are shown in greater detail in Figure 2. Mount Shasta (MS) and Lassen Peak (LP) denoted by stars.

Figure 2. Active faults of the Walker Lane (left) and San Andreas (right) fault systems. Historical earthquake surface ruptures are also annotated and shown by bold lines. Mount Shasta (MS) and Mount Lassen (ML) denoted by stars.

Figure 3. Decomposition of plate motion vectors into components parallel to the average strike of the Walker Lane and Central San Andreas faults predicts fault perpendicular components of extension and contraction along the Walker Lane and San Andreas, respectively. Figure modified from Bennett et al. (2003). See text for discussion.

Figure 4. The oblique component of displacement along the transtensional and transpressional strike-slip systems of the Walker Lane and San Andreas, respectively, is taken up locally on normal and thrust faults which trend parallel to the main zones of shear.

Figure 5. Distribution of fault traces along sections of the central Walker Lane (upper) and southern San Andreas (lower) fault systems. Each region displays east-striking left-slip faults and clockwise crustal rotations. The pattern of faulting within the Central Walker Lane may be analogous to an earlier stage of development of the San Andreas system prior to accumulation of sufficient slip to produce a throughgoing San Andreas fault. Half-arrows show sense of lateral slip and curled arrows sense of vertical crustal rotations.

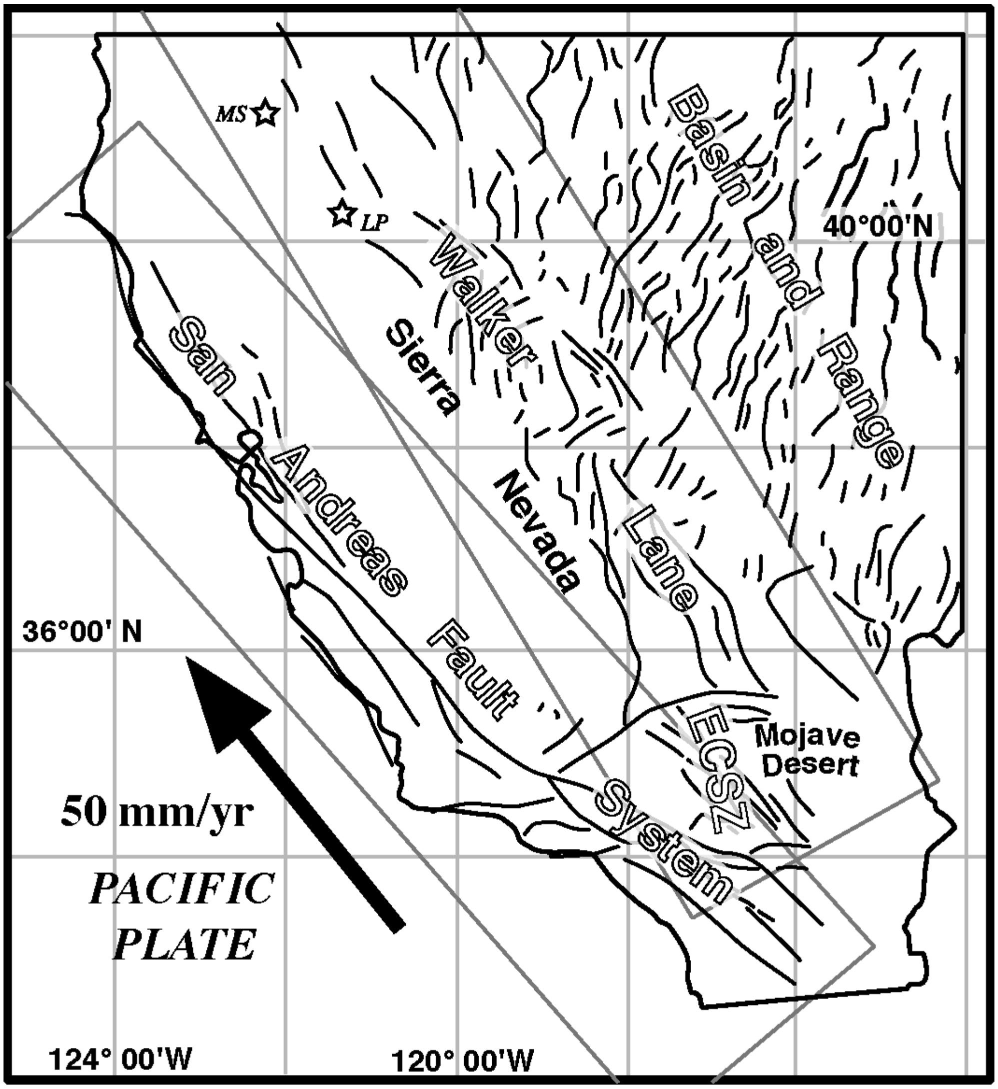
MS
LP
40°00'N
Basin and Range
Walker
Sierra
San
Andreas
Nevada
Lane
Fault
36°00' N
ECSZ
Mojave Desert
System
50 mm/yr
PACIFIC PLATE
124° 00'W
120° 00'W

Figure 1

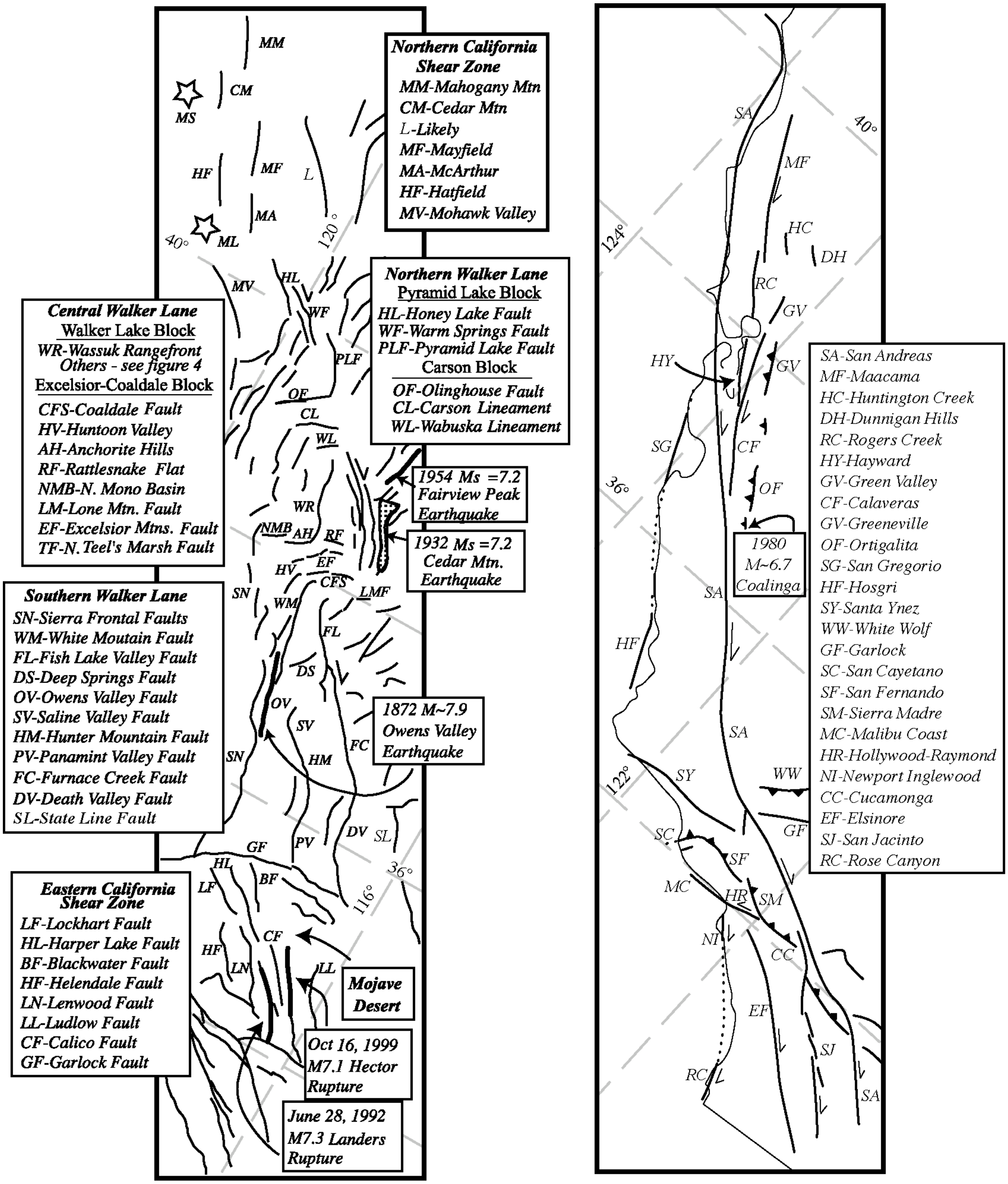
Northern California Shear Zone
MM-Mahogany Mtn
CM-Cedar Mtn
L-Likely
MF-Mayfield
MA-McArthur
HF-Hatfield
MV-Mohawk Valley
Northern Walker Lane
Pyramid Lake Block
HL-Honey Lake Fault
WF-Warm Springs Fault
PLF-Pyramid Lake Fault
Carson Block
OF-Olinghouse Fault
CL-Carson Lineament
WL-Wabuska Lineament
Central Walker Lane
Walker Lake Block
WR-Wassuk Rangefront
Others - see figure 4
Excelsior-Coaldale Block
CFS-Coaldale Fault
HV-Huntoon Valley
AH-Anchorite Hills
RF-Rattlesnake Flat
NMB-N. Mono Basin
LM-Lone Mtn. Fault
EF-Excelsior Mtns. Fault
TF-N. Teel's Marsh Fault
Southern Walker Lane
SN-Sierra Frontal Faults
WM-White Moutain Fault
FL-Fish Lake Valley Fault
DS-Deep Springs Fault
OV-Owens Valley Fault
SV-Saline Valley Fault
HM-Hunter Mountain Fault
PV-Panamint Valley Fault
FC-Furnace Creek Fault
DV-Death Valley Fault
SL-State Line Fault
Eastern California Shear Zone
LF-Lockhart Fault
HL-Harper Lake Fault
BF-Blackwater Fault
HF-Helendale Fault
LN-Lenwood Fault
LL-Ludlow Fault
CF-Calico Fault
GF-Garlock Fault
1954 Ms =7.2 Fairview Peak Earthquake
1932 Ms =7.2 Cedar Mtn. Earthquake
1872 M~7.9 Owens Valley Earthquake
Mojave Desert
Oct 16, 1999 M7.1 Hector Rupture
June 28, 1992 M7.3 Landers Rupture
MS
ML
40°
120°
36°
116°
SA-San Andreas
MF-Maacama
HC-Huntington Creek
DH-Dunnigan Hills
RC-Rogers Creek
HY-Hayward
GV-Green Valley
CF-Calaveras
GV-Greeneville
OF-Ortigalita
SG-San Gregorio
HF-Hosgri
SY-Santa Ynez
WW-White Wolf
GF-Garlock
SC-San Cayetano
SF-San Fernando
SM-Sierra Madre
MC-Malibu Coast
HR-Hollywood-Raymond
NI-Newport Inglewood
CC-Cucamonga
EF-Elsinore
SJ-San Jacinto
RC-Rose Canyon
1980 M~6.7 Coalinga
124°
122°

Figure 2

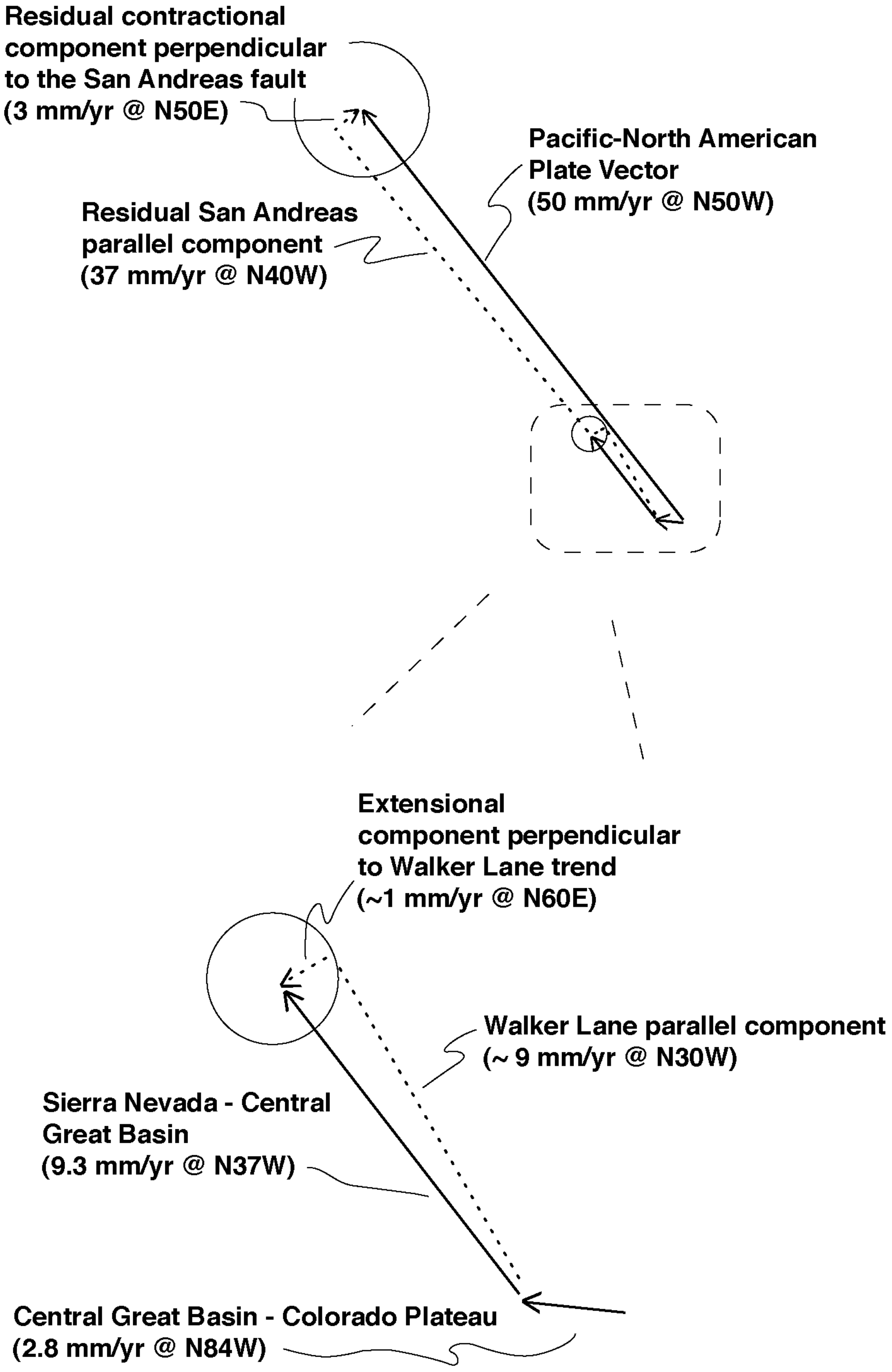
Residual contractional component perpendicular to the San Andreas fault (3 mm/yr @ N50E)
Pacific-North American Plate Vector (50 mm/yr @ N50W)
Residual San Andreas parallel component (37 mm/yr @ N40W)
Extensional component perpendicular to Walker Lane trend (~1 mm/yr @ N60E)
Walker Lane parallel component (~ 9 mm/yr @ N30W)
Sierra Nevada - Central Great Basin (9.3 mm/yr @ N37W)
Central Great Basin - Colorado Plateau (2.8 mm/yr @ N84W)

Figure 3

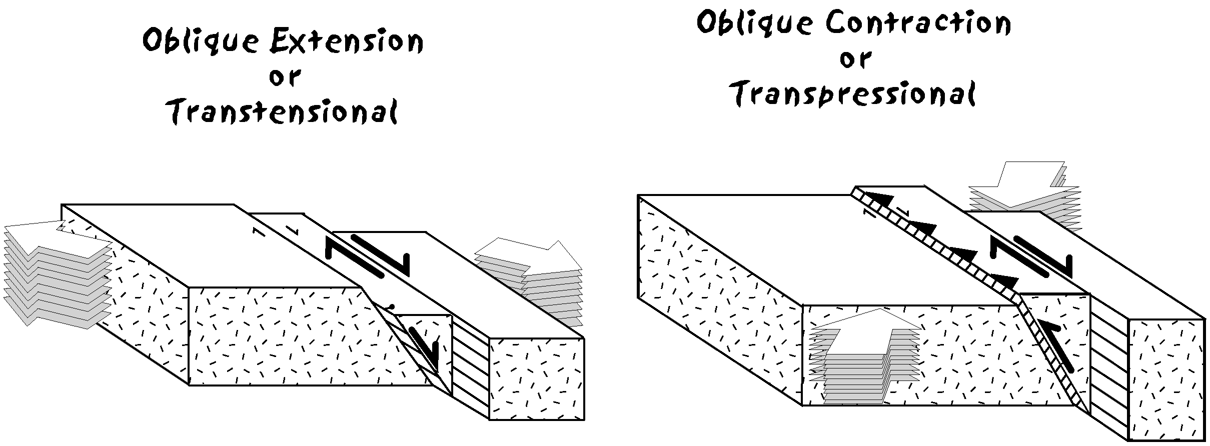
Oblique Extension
or
Transtensional
Oblique Contraction
or
Transpressional

Figure 4

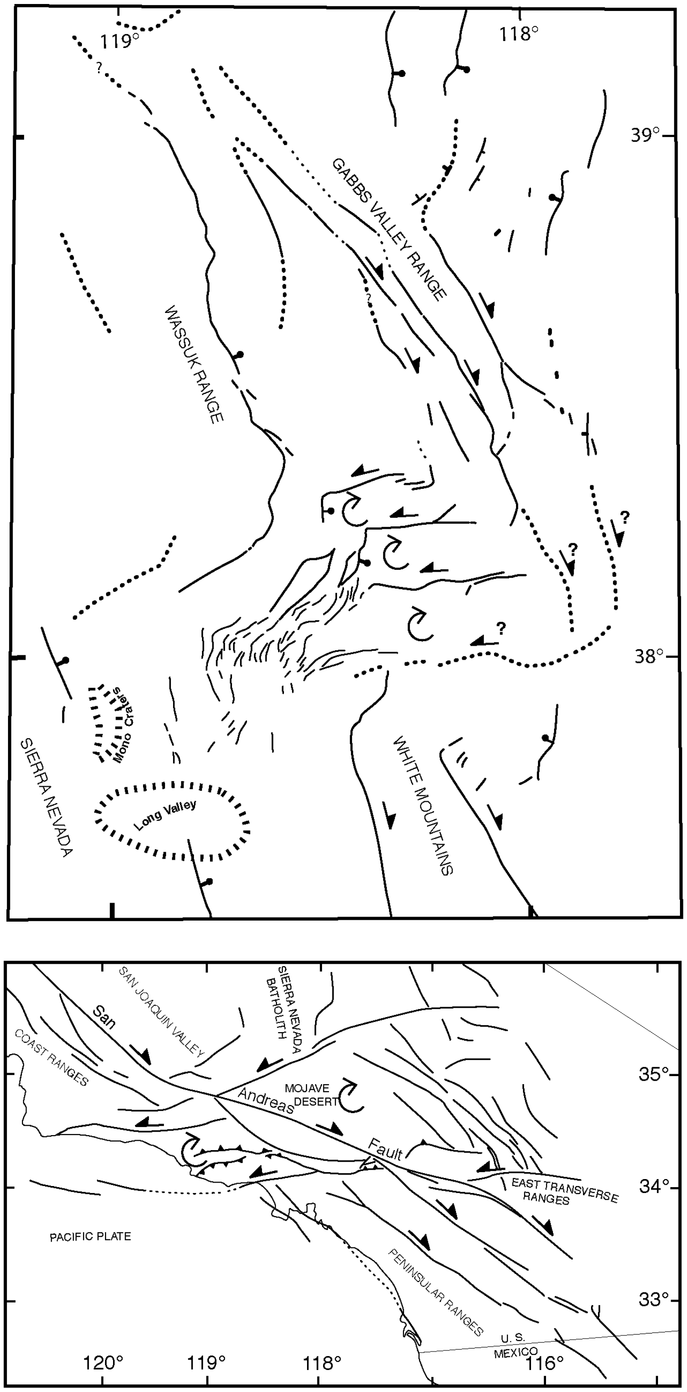
119°
118°
39°
38°
GABBS VALLEY RANGE
WASSUK RANGE
?
?
?
?
Mono Craters
SIERRA NEVADA
Long Valley
WHITE MOUNTAINS
SAN JOAQUIN VALLEY
SIERRA NEVADA BATHOLITH
San
COAST RANGES
MOJAVE DESERT
Andreas
Fault
EAST TRANSVERSE RANGES
35°
34°
33°
PACIFIC PLATE
PENINSULAR RANGES
U. S.
MEXICO
120°
119°
118°
116°

Figure 5