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Modern strain localization in the central Walker Lane, western United States: Implications for the evolution of intraplate deformation in transtensional settings

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ABSTRACT

Approximately 25% of the differential motion between the Pacific and North American plates occurs in the Walker Lane, a zone of dextral motion within the western margin of the Basin and Range province. At the latitude of Lake Tahoe, the central Walker Lane has been considered a zone of transtension, with strain accommodated by dip-slip, strike-slip, and oblique-slip faults. Geologic data indicate that extension and strike-slip motion are partitioned across the central Walker Lane, with dip-slip motion resulting in E–W to ESE–WNW extension along the present-day western margin of the central Walker Lane since approximately 15 Ma, and dextral strike-slip motion across a zone further east since as early as 24 Ma. GPS velocity data suggest that present-day strain continues to be strongly partitioned and localized across the same regions established by geologic data. Velocity data across the central Walker Lane suggest a minimum of 2 mm/yr extensional strain focused along the western margin of the belt, with very little extension across either the central or eastern portions of the Walker Lane. These data indicate very little dextral motion across the central and western portions of the domain, with dextral motion of 3–5 mm/yr presently focused along a discrete zone of the eastern part of the central Walker Lane, coincident with existing, mapped strike-slip faults. Historic seismic data reveal little seismic activity in areas of Late Holocene dip-slip motion in the west or dextral motion in the east, suggesting a period of quiescence in the earthquake cycle and the likelihood of future activity in both areas. Based on this and previous studies, it is likely that a combination of pre-Cenozoic crustal structure, a relatively weak lithosphere beneath the Walker Lane, and long-term low stress ratios in the crust have permitted the long-term partitioning of dextral and extensional strain exhibited across the central Walker Lane. The present-day location of dextral strain in the central Walker Lane is subparallel with dextral deformation documented in the northern Walker Lane, suggesting that as strain continues to accumulate, these two discrete zones could become a continuous strike-slip system which will play a more important role in the future accommodation of relative Pacific–North American plate motion.

1. Introduction

Relative motion between the North American and Pacific plates has resulted in a broad zone of distributed dextral shear on the western margin of North America (e.g., Atwater, 1970; Atwater and Stock, 1998). While most of this motion has been accommodated by the San Andreas strike-slip fault system (e.g., Bennett et al., 1999; DeMets and Dixon, 1999), GPS data indicate that faults in the western Basin and Range province account for approximately 25% of the total strain between the Pacific and North American plates (Minster and Jordan, 1987; Dixon et al., 1995; Bennett et al., 1999). South of latitude 36°N, most of this relative plate motion is accommodated within 100–200 km of the San Andreas fault (Bennett et al., 1999), but further north, through-going deformation associated with dextral motion also occurs to the east of the Sierra Nevada, along the Walker Lane belt (Fig. 1), separated from the San Andreas fault system by the Sierra Nevada–Great Valley microplate (e.g., Argus and Gordon, 1991).

The central Walker Lane (Fig. 1) is the locus for both dextral motion associated with the North American–Pacific plate boundary as well as significant extension associated with classic Basin and Range deformation. The pattern of faulting within the Walker Lane is more complex than that associated with the San Andreas system and might be the result of both the lower total cumulative dextral slip along the Walker Lane relative to the San Andreas as well as the different associated stress field of the Walker Lane (extensional) relative to the San Andreas (contractional) (e.g., Wesnousky, 2005a). Numerous geologic and geodetic studies of the Walker Lane reveal conflicting interpretations of how strain is accommodated across the region. Flesch et al. (2000) and Bennett et al. (2003) suggest distributed dextral shear and extension across the Walker Lane at most latitudes, while Oldow (2003) and Hammond and Thatcher (2004) hypothesize a zone of dextral-dominated transtension in the east and a zone of extension-dominated transtension in the west. Unruh et al. (2003) suggest focused dextral deformation along the entire Sierra Nevada

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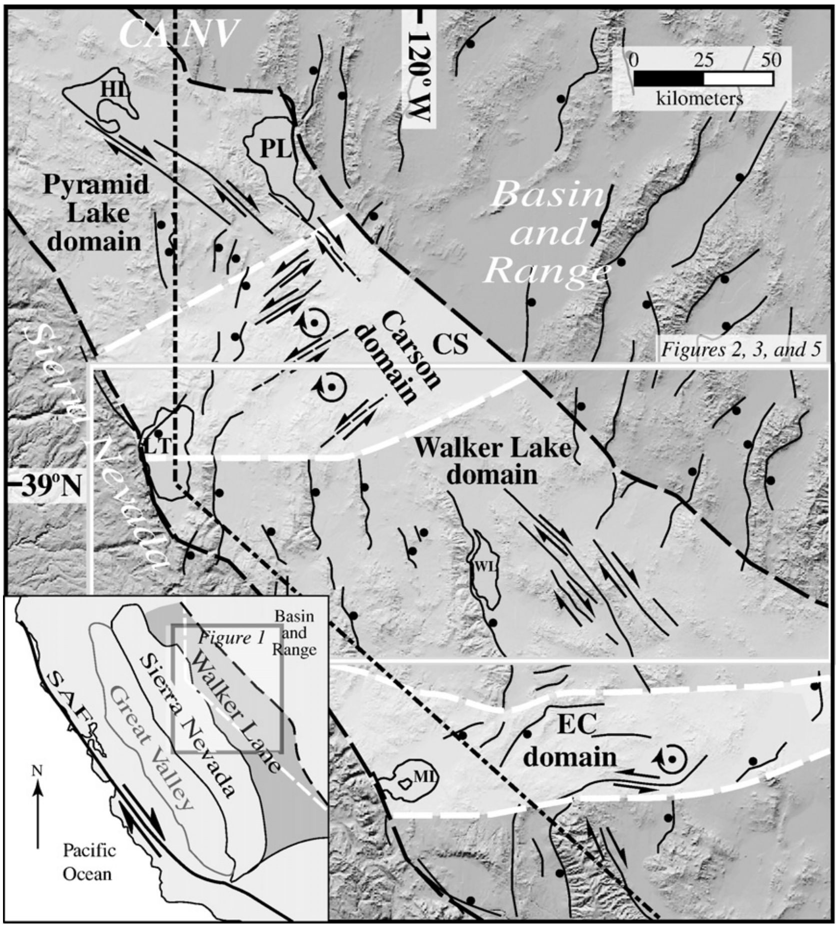

Fig. 1. Digital shaded relief map and location map of the central and northern Walker Lane showing the four structural domains of Stewart (1988), separated by dashed white lines, and the major normal and strike-slip faults in each domain. Sense of motion is indicated on all faults. Block rotations discussed in text are indicated. The region shown in Figs. 2, 3, and 5 is boxed in white. The bold, black, dashed lines indicate the boundaries of the Walker Lane as delineated by Stewart (1988). Abbreviations: EC — Excelsior — Coaldale; HL — Honey Lake; PL — Pyramid Lake; LT — Lake Tahoe; WL — Walker Lake; ML —Mono Lake; CS — Carson Sink; and SAF — San Andreas fault (modified after Ichinose et al., 1998).

range front fault system, with extension proximal to the range front related to northwestward migration of the Sierra Nevadan microplate, rather than Basin and Range extension.

Integrating previous geologic and seismic studies with recently published Global Positioning System (GPS) velocity data helps resolve this controversy. These data show a clear partitioning of present-day strain, with localization of most dextral deformation across a very narrow region in the eastern portion of the central Walker Lane and most extensional deformation focused in the west, proximal to the present-day Sierra Nevada range front fault system. These findings, combined with recent data from the northern Walker Lane, have significant implications for the evolution of intraplate deformation in transtensional settings and provide evidence for the future of the Walker Lane in the context of Pacific–North American plate interactions.

2. Geologic setting of the central Walker Lane

2.1. Structural domains of the central and northern Walker Lane

The Walker Lane is a complex zone of dextral and extensional deformation subdivided into structural domains based on the dominant mode of faulting in each domain (Fig. 1; Stewart, 1988). North of latitude 38°N, the domains are the Excelsior–Coaldale domain, the Walker Lake domain, the Carson domain, and the Pyramid Lake domain. Although dextral strike-slip faults have not been documented in all domains (Fig. 1), models of deformation based on geologic and geodetic data emphasize the importance of dextral deformation across all domains (e.g., Cashman and Fontaine, 2000; Oldow, 2003; Unruh et al., 2003; Hammond and Thatcher, 2004; Faulds et al., 2005).

The Excelsior–Coaldale domain is not cut by any through-going dextral faults (e.g., Stewart, 1993; Oldow, 1993) and is hypothesized to have been the locus of north–south directed extension related to the transfer of dextral displacement from the southern Walker Lane to the central Walker Lane in the north (e.g., Oldow et al., 1994). This domain is now thought to be the location where significant left-lateral strike-slip faults accommodate clockwise rotation of fault blocks about a vertical axis (e.g., Freund, 1974; Nur et al., 1986; Petronis et al., 2002; Wesnousky, 2005b), consistent with dextral motion along the eastern region of the Walker Lane belt (Fig. 1). The position of displacement transfer structures in the Excelsior–Coaldale domain might be related to the position of the continental edge during the Paleozoic, based on isotopic studies across the region (e.g., Kistler, 1991; Oldow et al., 1994).

The Walker Lake domain displays both well-defined northwest-striking dextral strike-slip faults in the east and major subparallel N–NNW-striking Basin-and-Range-style normal faults, in the western part of the domain (Figs. 1 and 2A). The timing of initiation of extensional faulting and associated deformation at this latitude becomes younger to the west (e.g., Dilles and Gans, 1995; Schweickert et al., 2000; Stockli et al., 2002; Surpless et al., 2002), so is relatively immature relative to the onset of dextral faulting in the eastern part of the domain or normal faulting in the Basin and Range further east. This younger deformation in the west may explain some of the structural complexity across the region.

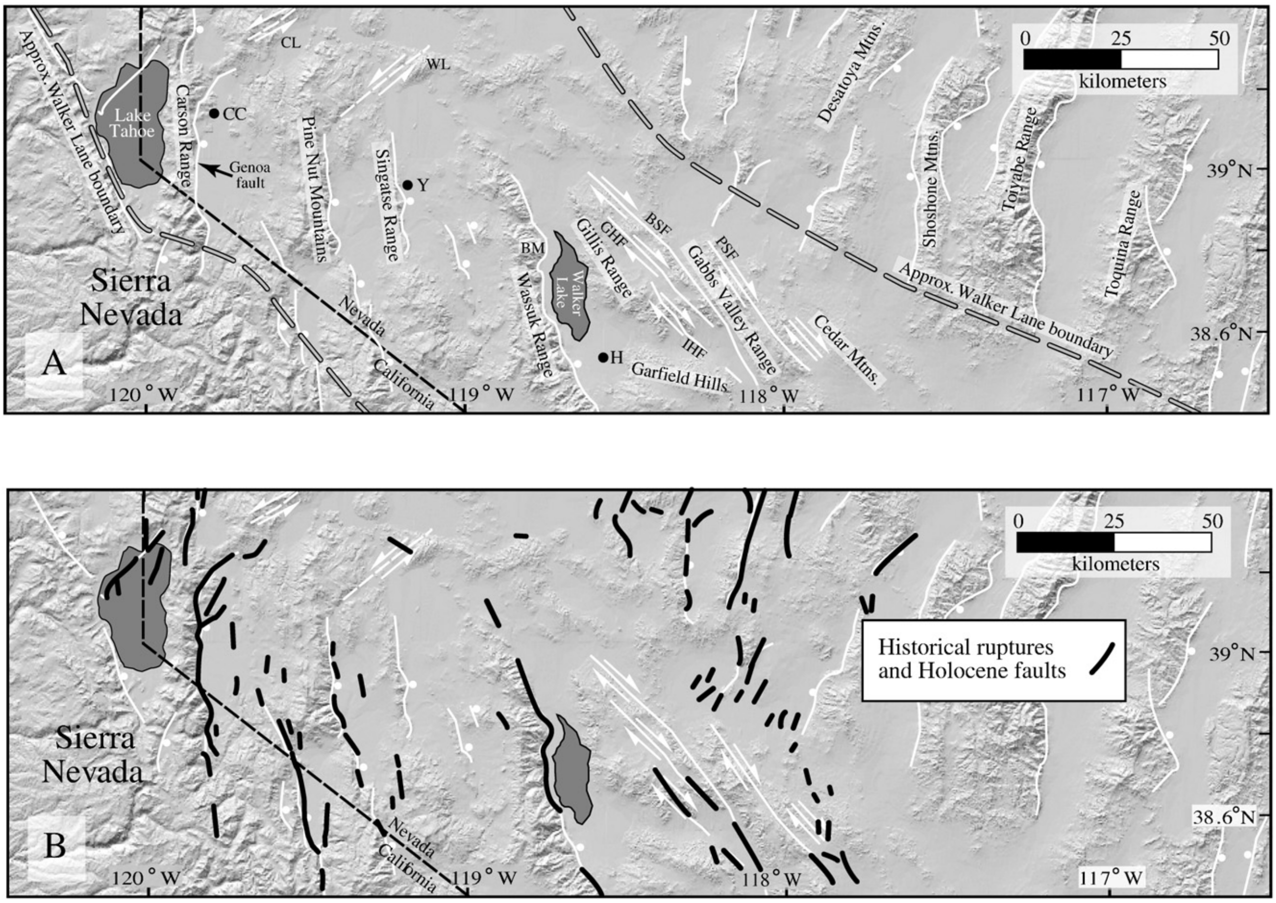

Fig. 2. A: Digital topography and geographical features of the Walker Lake domain. Faults are displayed as white lines and sense of motion is indicated on all major faults. The approximate location of the Walker Lane boundary is modified from Stewart (1988). Abbreviations: BM — Bald Mountain; BSF — Benton Spring Fault; CC — Carson City; CL — Carson lineament; GHF — Gumdrop Hills fault; H — Hawthorne; IHF — Indian Hills fault; PSF — Petrified Springs fault; WL — Wabuska lineament; and Y — Yerington. B: Historical ruptures and Holocene faults. Locations of historical ruptures and Holocene faults from Bell et al. (2004) and USGS and NBMG (2007).

The Carson domain is in part characterized by a lack of through-going dextral deformation (e.g., Slemmons et al., 1979; Stewart, 1993), but northeast-trending zones of sinistral faults are probably related to significant clockwise block rotations about a vertical axis caused by dextral motion associated with the Walker Lane (Cashman and Fontaine, 2000). These 35–44° block rotations (Cashman and Fontaine, 2000) are consistent with dextral deformation in the Carson Sink area to the east, where the gap exists between mapped dextral faults in domains to the south and north (Fig. 1).

The Pyramid Lake domain, at the northern end of the Walker Lane belt, displays five major northwest-striking dextral faults, with normal faults present in the western part of the domain (e.g., Bell and Slemmons, 1979; Bell, 1984; Faulds et al., 2005). The timing of initiation of dextral faulting is more recent in the Pyramid Lake domain than in the Walker Lake domain (e.g., Stewart, 1993), suggesting northward growth of the dextral system with time (e.g., Faulds et al., 2005). The pattern of faults and deformation at the northernmost extent of the Walker Lane suggests incipient strike-slip faulting to the north of mapped dextral faults, consistent with the hypothesized growth of the dextral system (Faulds et al., 2005).

2.2. Detailed geology of the Walker Lake structural domain

Within the Walker Lake domain, previous geologic studies have been able to constrain Miocene and younger normal and dextral motion. In the western part of the Walker Lake domain, Miocene and younger deformation has been accommodated by E–W directed extension along major N–NNW-striking normal faults (e.g., Stewart and Dohrenwend, 1984; Proffett and Dilles, 1984; Surpless, 1999; Stockli et al., 2002; Schweickert et al., 2004). In the eastern zone of the Walker Lake domain, dextral faults trend ~N25–50°W (Fig. 2A), subparallel to the overall trend of the Walker Lane, and there is little evidence for significant extensional deformation (e.g., Ekren et al., 1980; Ekren and Byers, 1984; John, 1992).

2.3. Western section of the Walker Lake domain

In the western section of the Walker Lake domain, the locus of significant extensional deformation migrated to the west from the Wassuk Range at ~15 Ma to the Sierra Nevada frontal fault system at ~3 Ma (Dilles and Gans, 1995; Henry and Perkins, 2001; Surpless et al., 2002; Schweickert et al., 2004), although the timing of the onset of faulting related to Sierra Nevadan uplift might be much earlier than 3 Ma (e.g., DeOreo et al., 2005). The motion along a series of N–NNW-striking, east-dipping normal faults is primarily dip-slip (e.g., Proffett, 1977; Dilles, 1993; and Surpless et al., 2002), resulting in a series of asymmetric half-grabens and mountain ranges across the area (Fig. 2A).

In the Wassuk Range and the Singatse Range (Fig. 2A), the onset of extension is closely linked to calc-alkaline volcanism associated with the ancestral Cascade arc at ~15 Ma and younger (e.g., Proffett, 1977; Dilles, 1993; Surpless et al., 2002; Stockli et al., 2002). Thermochronologic analysis suggests a major extensional event affected both ranges between ~15 and ~12 Ma, with a later period of lower-magnitude extension deforming the eastern flank of the Wassuk Range (Stockli et al., 2002; Surpless et al., 2002).

The impressive topographic relief, the development of well-defined triangular facets, and numerous fault-slip indicators along the range-bounding fault of the Wassuk Range suggest present-day ESE–WNW to E–W directed extension and normal faulting, with no evidence for dextral deformation (Zoback, 1989; Surpless, 1999). Wesnousky (2005b) documents continued normal fault activity along the east flank of the Wassuk Range, with evidence of significant dip-slip displacement in the last 5000 years. Demsey (1987) suggests two major earthquake events along the Wassuk Range fault zone, with the most recent occurring along the east flank of the northern Wassuk Range at ~2.5 ka (rupture length of 50 km and M 7.2–7.5), and an older event along the east flank of the southern Wassuk Range at ~4.5 ka (rupture length of 30 km and M 7.0–7.1). Demsey (1987) calculated a slip rate of 0.4–0.5 mm/yr for the northern portion of the Wassuk Range fault system. Although most of the range-bounding fault system has been active in the recent past, there is no evidence for significant Holocene displacement along a 10 kilometer fault segment to the south of Walker Lake (Fig. 2B). Mountain-front morphometric and stream-gradient analyses along the entire Wassuk Range imply that the northern section has been more tectonically active, with a preferred slip rate of 0.4–0.5 mm/yr, than the southern section throughout the Quaternary (Demsey, 1987; Demsey et al., 1988).

Further west, the range-bounding fault system of the Singatse Range displays no evidence for geologically-recent significant dip-slip displacement, with no part of the fault system displaying any movement during the Holocene (Fig. 2B; Bell et al., 2004; USGS and NBMG, 2007). In the Pine Nut Mountains, thermochronologic data suggest that the onset of normal faulting is more recent than ~10 Ma (Surpless et al., 2002), with discontinuous segments of the fault system displaying Holocene motion (Fig. 2B; Bell et al., 2004; USGS and NBMG, 2007). Gilbert and Reynolds (1973) hypothesize that a portion of extensional strain has been accommodated by folding across the western section, adjacent to the Pine Nut Mountains and the Singatse Range.

The principal faults of the Sierra Nevada range front fault system, including the Genoa fault (Fig. 2A), display dominantly east-side-down displacements that cut volcanic rocks as young as 3.6 Ma (Schweickert et al., 2000). All segments of the Genoa fault have been active during Holocene time (Fig. 2B; Bell et al., 2004; USGS and NBMG, 2007), and Zoback (1989) used fault-slip and focal mechanism data to suggest that dip-slip motion along the Genoa fault accommodates present-day east–west directed extension. Ramelli et al. (1999) document two significant episodes of dip-slip motion (3.0–5.5 m slip per event) during Late Holocene time, with the last event occurring between 1000 and 4000 yr B.P., indicating very recent and significant normal dip-slip displacement of the fault. These data suggest an apparent late Holocene slip rate of 2–3 mm/yr along the Genoa fault, one of the highest slip rates in the Basin and Range province (Ramelli et al., 1999).

West of the Genoa fault, to the west of Lake Tahoe, normal faults accommodate up to 72 m dip-slip displacement of Tahoe age (~56–118 ka) moraine crests (Schweickert et al., 2000). In addition, faults within the lake itself display Holocene motion (Fig. 2B; USGS and NBMG, 2007), and Wakabayashi and Sawyer (2001) document incipient extensional deformation in the Sierra Nevada to the west of the Lake Tahoe region. These studies indicate that Basin and Range extension continues to migrate west into the relatively unextended Sierra Nevada block (e.g., Surpless et al., 2002).

In the northern Wassuk Range, northwest-striking faults with dextral motion were active during the peak of ancestral Cascades volcanism, but geological evidence for modern Walker Lane dextral deformation is limited to a northwest-striking zone northeast of the northern Wassuk Range and to areas further east (Dilles, 1993). In the central Wassuk Range, a poorly-exposed NW-striking dextral fault with minor (<800 m) horizontal offset (Bingler, 1978; Surpless, 1999) displaces syntectonic sediments of the Wassuk Group, deposited between 10 and 8–7 Ma (Dilles, 1993), but the fault could not be traced laterally and displays no evidence of recent movement (Surpless, 1999). There is sparse evidence for right-lateral motion along the Sierra Nevada range front, but the magnitude and timing of this motion is not constrained by geologic data (e.g., Wakabayashi and Sawyer, 2001; Schweickert et al., 2004).

2.4. Eastern section of the Walker Lake domain

To the east of the Wassuk Range, the Gabbs Valley Range and the Gillis Range exhibit lower topographic relief relative to ranges in the western section, display little dip-slip deformation associated with extension, and are cut by a through-going system of dextral faults which may have been active as early as 24 Ma (Fig. 2A; e.g., Ekren et al., 1980; Ekren and Byers, 1984; John, 1992), with most motion taking place since 15–10 Ma years (e.g., Hardyman and Oldow, 1991; Oldow et al., 1994). These faults, including the Gumdrop Hills fault, the Indian Head fault, the Benton Springs fault, and the Petrified Springs fault (Fig. 2A), accommodated as much as 80 km of dextral displacement, based on offsets of Tertiary tuffs and lavas as well as older granitic rocks and volcaniclastics (e.g., Ekren et al., 1980; Ekren and Byers, 1984; John, 1992; Stewart, 1993; Wesnousky, 2005b).

Today, the Benton Springs and Petrified Springs faults are the most important structures accommodating dextral motion in the Walker Lane, but all of these dextral faults remain active (e.g., Stewart, 1993; Wesnousky, 2005b) and display Holocene movement along portions of their lengths (Fig. 2B; Bell et al., 2004; USGS and NBMG, 2007). This system of dextral faults is linked with dextral motion of the southern Walker Lane belt to the south (Fig. 1) by a structurally complex system of both dip-slip and oblique-slip faults in the Exelsior–Coaldale domain (Fig. 1) (Oldow, 1993; Oldow and Aiken, 1998; Oldow et al., 1998). Deformation in this transfer zone has taken place almost entirely within the past 12–15 Ma (e.g., Hardyman and Oldow, 1991; Dilles and Gans, 1995).

In the Carson domain to the northwest, no through-going dextral faults occur along strike of the dextral faults of the Walker Lake domain (Fig. 1). However, the clockwise fault-block rotations in the Carson domain began by 9–13 Ma, with a sense of rotation compatible with dextral motion (Fig. 1; Cashman and Fontaine, 2000). These geologic data suggest that fault-block rotations in the Carson domain and deformation in the Excelsior–Coaldale domain were synchronous with dextral deformation within the eastern section of the Walker Lake domain.

2.5. Boundary between the eastern and western sections of the Walker Lake domain

The timing of activity across both zones of the Walker Lake domain implies that predominantly dip-slip extensional faulting in the western section of the domain occurred concurrently with dextral motion in the Gabbs Valley and Gillis Ranges of the eastern section of the domain since the Miocene. Recent studies indicate that this east–west partitioning of strain has continued to the present (e.g., Ramelli et al., 1999; Wesnousky, 2005b), with the east-dipping normal fault on

Fig. 3. A: Global positioning system station sites and total velocity vectors from the Walker Lake domain. Velocities are in fixed North American reference frame. Ellipses shown are either 95% confidence (Oldow, 2003) or +/−2σ (USGS Earthquake Hazards Program, 2006). From west to east, the zones are: Lake Tahoe (LT — white vectors), Wassuk Range (WR — black vectors), Gabbs Valley Range (GVR — white vectors), and Basin and Range (BR — black vectors). Thick, white, dashed lines are the approximate locations of divisions between velocity zones. Data are summarized in Table 2. B: Dextral components of velocity vectors (v_{dex}), subparallel to the North American–Pacific plate boundary at this latitude (~N35° W). Details of the vector calculation are shown in Fig. 4. C: N35°W component of GPS velocities (v_{dex}) with respect to stable North America as a function of distance from Hawthorne, Nevada, measured in the direction N65°E (N25°W = approximate orientation of zone boundaries). Approximate position of dextral faults of the Gabbs Valley and Gillis Ranges indicated by shaded grey box. D: Extensional components of velocity vectors (v_{ext}), based on the component of velocity that remains after the dextral component is removed. Details of vector calculation are shown in Fig. 4.

the east flank of the Wassuk Range marking the western boundary of the active dextral motion of the Walker Lane at this latitude (e.g., Wesnousky, 2005b). The position of the boundary between dominantly extensional and dominantly dextral strain fields in the Walker Lake domain might be at least partly controlled by pre-Cenozoic crustal structure, as suggested for the bend in late-Cenozoic structures

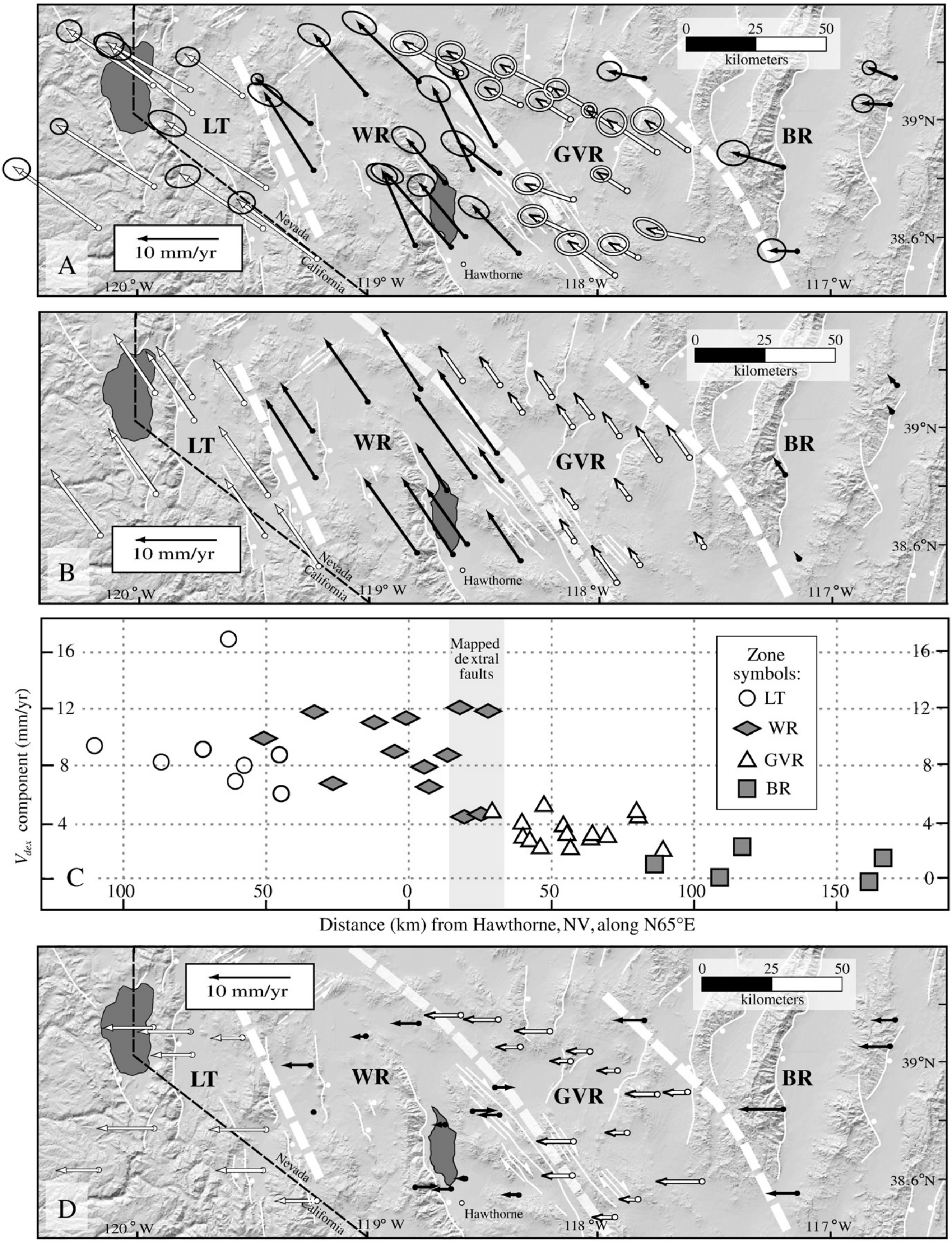

Table 1
GPS stations and velocity data from the Walker Lake domain

Station	Lat. (N)	Long. (W)	V_n	V_w	V_{dex}	V_{ext}
Lake Tahoe Zone						
H112	38.63339	120.1767	7.65	10.51	9.34	5.15
A300	38.77725	119.9241	7.48	11.89	9.13	6.65
P208	38.11082	119.9227	6.77	10.3	8.26	5.56
A250	39.10145	119.7742	5.65	9.96	6.90	6.00
V209	39.08299	119.5439	4.83	6.63	5.90	3.25
SWWS	38.53046	119.2174	7.1	9.47	8.67	4.50
Oldow (2003)	39.02	119.76	13.9	14.3	16.9	4.6
Oldow (2003)	38.77	119.44	8.1	12.2	9.9	6.5
Oldow (2003)	38.63	119.46	6.5	9.9	7.9	5.3
		Average	7.6	10.6	9.2	5.3
		Std. dev.	2.58	2.13	3.14	1.08
		Variance	6.63	4.56	9.89	1.16
Wassuk Range Zone						
B300	38.98812	119.2441	5.51	6.7	6.73	2.84
W078	38.60609	118.5769	6.5	5.45	7.94	0.90
Oldow (2003)	38.83	119.24	9.6	6.0	11.7	−0.7
Oldow (2003)	39.09	119.00	7.4	6.4	9.0	1.3
Oldow (2003)	38.57	118.80	9.0	3.9	11.0	−2.5
Oldow (2003)	39.13	118.78	7.1	7.3	8.7	2.3
Oldow (2003)	38.78	118.74	5.3	4.6	6.5	0.9
Oldow (2003)	38.57	118.64	9.3	8.1	11.3	1.6
Oldow (2003)	38.83	118.55	9.9	4.7	12.1	−2.2
Oldow (2003)	38.91	118.45	9.7	5.3	11.8	−1.4
Oldow (2003)	38.82	118.43	3.8	4.9	4.7	2.2
Oldow (2003)	38.55	118.34	3.6	4.9	4.3	2.4
		Average	7.2	5.7	8.8	0.6
		Std. dev.	2.31	1.2	2.82	1.88
		Variance	5.32	1.53	7.93	3.54
Gabbs Valley Range Zone						
SNDS	39.14751	118.4225	3.11	5.9	3.80	3.72
SHEL	39.04319	118.3245	1.99	3.94	2.43	2.55
SLR1	39.10917	118.2061	2.89	5.95	3.53	3.93
AGGI	39.0032	118.1264	2.33	3.76	2.84	2.13
FT73	38.73066	118.1039	1.73	5.29	2.11	4.08
POST	39.03592	118.0356	2.45	4.21	2.99	2.49
GABB	38.97033	117.9164	2.31	3.55	2.82	1.93
C300	38.75992	117.8839	2.11	3.32	2.58	1.84
CEDA	38.53124	117.8235	1.67	3.17	2.04	2.00
Oldow (2003)	39.16	118.59	3.8	6.9	4.7	4.2
Oldow (2003)	38.61	118.11	2.2	5.0	2.7	3.5
Oldow (2003)	38.46	117.94	4.1	5.5	5.1	2.6
Oldow (2003)	38.89	117.75	3.8	5.8	4.6	3.2
Oldow (2003)	38.59	117.56	1.5	6.7	1.8	5.6
Oldow (2003)	38.90	117.62	3.6	4.9	4.3	2.4
		Average	2.6	4.9	3.2	3.1
		Std. dev.	0.85	1.21	1.04	1.08
		Variance	0.73	1.45	1.09	1.16
Basin and Range Zone						
BUFF	39.14594	117.8068	0.91	4.25	1.11	3.61
MAHH	38.55247	117.1332	0.07	4.23	0.09	4.18
D300	39.05616	116.7457	−0.13	3.41	−0.16	3.50
MONI	39.14771	116.7156	1.20	3.01	1.46	2.17
Oldow (2003)	38.84	117.20	1.9	6.1	2.3	4.7
		Average	1.5	4.5	1.9	3.5
		Std. dev.	0.47	2.15	0.57	1.82
		Variance	0.22	4.62	0.32	3.32

Sources of data:
All data were calculated in the ITRF96 (International Terrestrial Reference Frame) realization and fixed in a North American Reference frame. All named GPS station data (e.g., H112) are from the USGS Earthquake Hazards Program (2006). All other data are estimated from Oldow (2003). Where duplicate stations exist, the USGS data were used. See data sources for discussion of error.

in the Excelsior–Coaldale domain to the south (e.g., Wetterauer, 1977; Cogbill, 1979; Oldow et al., 1994), which separates the southern and central Walker Lane (e.g., Oldow et al., 1994). This hypothetical crustal boundary is based primarily on the position of the 0.706 isotope line, which is hypothesized to separate Paleozoic continental from non-continental crust (e.g., Kistler, 1991).

3. Distribution of modern strain in the Walker Lake domain

Previous Very Long Baseline Interferometry (VLBI) and GPS studies support the conclusion that contemporary Basin and Range deformation is concentrated along the western margin of the province (e.g., Argus and Gordon, 1991; Dixon et al., 1995; Bennett et al., 1998; Thatcher et al., 1999). Although geodetic data are inherently limited by the short timeframe for which velocities have been measured as well as by the uneven distribution of GPS stations, Hammond and Thatcher (2004) use GPS velocity data to subdivide deformation in the Walker Lane into two general zones. One zone, within the central portion of the Walker Lane, is dominated by right-lateral simple shear, and the other zone, along the Sierra Nevada frontal fault system, is characterized by shear with a component of extensional deformation. Similarly, Oldow (2003) uses original and previously published GPS data to subdivide the central Walker Lane into a zone of extension-dominated transtension on the west and wrench-dominated transtension on the east. Published GPS data across the Walker Lane now permit a more detailed analysis of present-day deformation of the Walker Lake domain in the context of the documented geology.

Velocity data presented here include two-dimensional GPS velocity data from the USGS Earthquake Hazards Program (2006) and GPS data graphically analyzed from Oldow (2003). These data are geographically limited to the Walker Lake domain and areas immediately adjacent to the Walker Lane belt, between latitudes 38.4°N and 39.4°N and longitudes 117.5°W and 120.2°W (Figs. 1 and 3A). GPS velocity vectors displayed in Table 1 and on Fig. 3A were calculated in the ITRF-96 (International Terrestrial Reference Frame) realization and fixed in a North American reference frame. Although the definition of stable North America differs between published results, including references cited by Oldow (2003), velocity solutions for shared sites are well within reported uncertainties and do not contribute statistically significant variability to the velocity data. A GPS velocity station located at ~38.95°N and ~118.15°W within the Gabbs Valley Range zone (from Oldow, 2003) was removed from the data set due to a strongly divergent orientation of the velocity vector relative to other local vectors. This station appears to record very localized strain and is in an area with a high enough density of GPS stations (Fig. 3A) that no significant information is considered lost.

The GPS data across the Walker Lake domain are here subdivided into four zones based on both station location and consistency of vector orientation (Table 1; Fig. 3A): the Lake Tahoe zone (LT); the Wassuk Range zone (WR); the Gabbs Valley Range zone (GVR); and the Basin and Range zone (BR). The magnitude of both northward and westward velocity components increases from east to west (Table 1; Fig. 3A), as is expected on the western margin of the Basin and Range province, where both dextral and extensional deformation have been well-established in the geologic record. The velocity components display abrupt changes in magnitude across relatively narrow regions, which appear to coincide with styles of deformation established by the earlier geologic history of the region.

The average northward velocity component (v_n) values are low in the Basin and Range zone (1.5 mm/yr) and increase slightly on the eastern margin of the Walker Lane in the Gabbs Valley Range zone (2.6 mm/yr). However, a significant and abrupt increase in the magnitude of the average v_n occurs between the Gabbs Valley Range zone (2.6 mm/yr) and the Wassuk Range zone (7.2 mm/yr) (Tables 1

Table 2
GPS velocity data summary, in mm/yr, from the Walker Lake domain

Zone	Ave. V_n	Ave. V_w	Ave. V_{dex}	Ave. V_{ext}		DV_{dex}	DV_{ext}
Lake Tahoe (LT)	7.6	10.6	9.2	5.3	LT – WR	0.4	4.1
Wassuk Range (WR)	7.2	5.7	8.8	1.2	WR – GVR	5.6	(-) 1.9
Gabbs Valley Range (GVR)	2.6	4.9	3.2	3.1	GVR – BR	1.3	(-) 0.4
Basin and Range (BR)	1.5	4.5	1.9	3.5			

Table 3
T-test results for comparison of GPS velocity data from zones listed in Tables 1 and 2

Zones compared	*t*-value				Degrees of freedom (n−2)	95% Confidence exceedance value (abs. value)
	v_n	v_w	v_{dex}	v_{ext}		
LT–WR	0.306	***6.133***	0.306	***7.142***	19	2.093
WR–GVR	***6.532***	1.636	***6.532***	***−3.988***	25	2.060
GVR–BR	***3.650***	0.387	***3.650***	−0.447	18	2.101

Zone abbreviations are the same as those shown in Table 2. All *T*-test analyses are based solely on the component values given (v_n and v_w) or calculated (v_{dex} and v_{ext}) and don't integrate measurement errors/2σ ellipses from published data. In the table above, n = total number of stations in both zones. Exceedance values (from a statistical *t*-value table) are based on the number of degrees of freedom ($n-2$) and probability (P = 0.05 or 95% confidence). A *t*-value (absolute value) that is greater than the 95% confidence exceedance value indicates a statistical difference between sample populations (shown in ***bold italics*** in the above table). A *t*-value that is below the exceedance value indicates sample populations that are not statistically different. The *t*-value formula for the comparison of two sample populations, A and B, is shown below. The denominator of the formula is also known as the standard error of difference of means.

$$t = \frac{\overline{X}_A - \overline{X}_B}{\sqrt{\frac{\mathrm{var}_A}{n_A} + \frac{\mathrm{var}_B}{n_B}}}$$

$\overline{X}_A$ = mean of population A.
var_A = variance of population (variance = square of S.D.).
n_A = total samples in population A.

and 2; Fig. 3B). This 4.6 mm/yr relative velocity difference is also obvious in graphic form (Fig. 3A) and appears to coincide with the mapped dextral faults of the Gillis and Gabbs Valley ranges. Further west, the magnitude of northward velocity increases only slightly (an average of 7.2 mm/yr in the Wassuk Range zone to an average of 7.6 mm/yr in the Lake Tahoe zone), suggesting little difference in northward motion of the Lake Tahoe zone relative to the Wassuk Range zone.

T-test analyses, which examine the statistical differences between adjacent zones, support these results (Table 3). The *T*-test technique permits evaluation of the mean velocity values for two zones (e.g., Lake Tahoe zone vs. Wassuk Range zone) relative to the variability of the two zones' velocity populations. If the difference between the means of two zones' sample populations is large relative to the variability of the two velocity populations, then the calculated *t*-value will exceed the 95% confidence *t*-value, suggesting that the means are statistically different. In contrast, if the calculated *t*-value for the statistical comparison of two velocity populations falls below the 95% confidence *t*-value, the variability of the populations is too great to demonstrate statistical difference between populations.

The northward velocity (v_n) *t*-value for the Wassuk Range (WR) and Gabbs Valley Range (GVR) confirms that the northward velocity values (v_n) for the two zones are very different statistically (Tables 2 and 3). The northward velocity *t*-value for the Gabbs Valley Range and Basin and Range (BR) populations also suggests a lesser, but statistically significant difference, but the northward velocity *t*-value for the Wassuk Range and Lake Tahoe (LT) populations indicates no statistical difference between northward velocity populations for those western zones (Table 3).

As noted with the northward components of GPS velocities, the relative differences in magnitudes of westward velocities (v_w) do not vary constantly across the Walker Lake domain (Table 1; Fig. 3A). In the eastern zones, the westward components of velocity change from an average of 4.5 mm/yr in the Basin and Range zone to an average of 4.9 mm/yr in the Gabbs Valley Range zone (Tables 1 and 2). *T*-test analysis of these westward velocity (v_w) populations suggests that these zone velocity populations are not statistically different (Table 3). A slight increase from an average of 4.9 mm/yr in the Gabbs Valley Range zone to 5.7 mm/yr in the Wassuk Range zone yields a *t*-value closer to the 95% confidence value than between the populations of the easternmost zones (Table 3), but the difference between zone populations is not statistically significant. The westernmost zones display the most significant change in the westward components of velocities. The nearly 5 mm/yr difference in average v_w between the Lake Tahoe (v_w = 10.6 mm/yr) and Wassuk Range (v_w = 5.7 mm/yr) zones (Tables 1 and 2) suggests that differential westward velocity is concentrated along the western margin of the Walker Lake domain, proximal to the Sierra Nevada range front; this observation is supported by the strong statistical difference between the two zones' westward velocity populations (Table 3).

While analyses of northward and westward components give a general idea about the present-day strain field across the Walker Lake domain, the established geologic structure of the region permits a more revealing analysis of modern deformation. Geologic structures at all scales (Figs. 1 and 2) reveal a dominant trend of ~N35°W. This trend is based on the approximate orientation of the Pacific–North American plate boundary at this latitude, the direction of motion of the Sierra Nevada–Great Valley microplate relative to the Basin and Range (Hammond and Thatcher, 2007), the trend of the central and northern Walker Lane, and the average trend of mapped dextral faults in the eastern Walker Lake domain (Figs. 1 and 2). In addition, the N–S strike of normal faults in the western Walker Lake domain (i.e., range - bounding faults of the Carson Range, the Pine Nut Mountains, and the Singatse Range) is consistent with an approximate E–W orientation of the maximum extensional strain rate (Hammond and Thatcher, 2007). Therefore, to better define the components of dextral and extensional strain, the total velocity vectors were split into two components (Figs. 3 and 4; Tables 1 and 2). The direction of the dextral component (v_{dex}) is parallel to N35°W, and the extensional velocity component (v_{ext}) is what remains when the dextral velocity component is subtracted from the total velocity vector (Figs. 3 and 4). Although other dextral and extensional directions could be chosen for analysis, the long-term structural evolution of the area suggests that the component directions chosen here are perhaps less arbitrary. In the cases of vectors with trends more northerly than N35°W, found in the Walker Lake zone, the extensional vectors become negative, directed eastward (Table 1; Fig. 3C). However, the extensional components of velocity still fall within the error ellipses (as calculated by Oldow, 2003) for those vectors (Fig. 3).

As suggested by the analysis of the northward components of velocity vectors, the dextral velocity vectors of stations across the Walker Lake domain (Fig. 3; Table 2) also indicate that present-day dextral deformation is localized along a very narrow region, perhaps 15–20 km across, within the eastern section of the Walker Lake domain and is virtually absent from the western section of the domain. The average dextral GPS velocity components (v_{dex}) of the Lake Tahoe zone and the Wassuk Range zone (9.2 mm/yr and 8.8 mm/yr, respectively) are nearly identical, within less than one standard deviation, suggesting no statistically significant dextral motion across the western

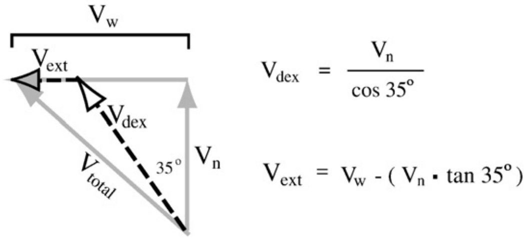

Fig. 4. Graphical representation of the calculation of the dextral (v_{dex}) and extensional (v_{ext}) components of the GPS velocity vectors of the Walker Lake domain. The northward and westward components of reported GPS velocity vectors were used to calculate the approximate component of plate–boundary parallel motion oriented ~N35 W (v_{dex}) and the remaining component, assumed to be a component of extension (v_{ext}). The resulting vectors are shown in Fig. 3. The calculated values for all GPS stations across the Walker Lake domain are displayed in Table 1, and the data are summarized in Table 2.

section of the block (Table 3). In contrast, there is a statistically significant difference in average v_{dex} between the Wassuk Range zone (WR) and the Gabbs Valley Range zone (GVR), from 8.8 mm/yr (WR) to 3.2 mm/yr (GVR) (Tables 2 and 3). This indicates relative dextral motion on the order of more than 5 mm/yr (Table 2) accommodated across a very narrow region about 15–20 km wide, which coincides with one or more of the dextral faults mapped across the Gillis and Gabbs Valley ranges (Figs. 2A and 3B). The relative difference in v_{dex} between the Gabbs Valley Range (GVR) zone and the Basin and Range (BR) zone, from 3.2 mm/yr (GVR) to 1.9 mm/yr (BR), also indicates minor, statistically significant, active dextral deformation on the eastern margin of the Walker Lake domain (Tables 2 and 3), supporting possible dextral deformation on the eastern margin of the Walker Lane at this latitude.

To better characterize geographic changes in the dextral velocity component, Fig. 3C displays dextral velocities (v_{dex}) relative to Hawthorne, Nevada (Fig. 3B), measured along the direction N65°E. This direction is approximately perpendicular to the zone boundaries (Fig. 3A and B), so is considered a good estimate of how v_{dex} varies with position across the central Walker Lane. The v_{dex} gradient from the easternmost station of the Basin and Range zone (BR) to the westernmost station of the Gabbs Valley Range (GVR) zone is relatively low, but does indicate a clear increase in v_{dex} with decreasing distance from Hawthorne (Fig. 3C), consistent with minor dextral deformation on the eastern margin of the Walker Lane, discussed above. The steepest velocity gradient across the Walker Lake domain occurs across the mapped dextral faults of the central Walker Lane, where station velocities jump from 2–4 mm/yr to the east of the faults to 7–12 mm/yr west of these faults (Fig. 3C). Tremendous variability exists within this zone of mapped faults (Fig. 3C), potentially caused by local variations in the accommodation of strain. Further west, both the Wassuk Range (WR) and Lake Tahoe (LT) zones display no consistent change in velocity with distance from Hawthorne (Fig. 3C), consistent with the statistical similarities between the stations of each zone (Tables 2 and 3). Based on this analysis, the minimum shear parallel to N35°W across the mapped dextral faults is ~3 mm/yr, slightly lower than the ~5 mm/yr shear based on mean velocity values. Further to the west, the Lake Tahoe (LT) zone displays no increase in dextral velocity with increasing distance from Hawthorne either between stations within the zone or relative to stations within Wassuk zone to the east (WR), suggesting that most dextral deformation is presently accommodated in the region proximal to the mapped faults of the Gabbs Valley and Gillis Ranges (Fig. 3C), consistent with comparison of zone means and variability discussed above (Tables 1 and 2; Fig. 3B).

Present-day extensional strain is of smaller magnitude than dextral deformation in the Walker Lake domain and appears to be concentrated within the western section of the domain. The 4.1 mm/yr relative difference between the average extensional velocity components (v_{ext}) of the Lake Tahoe (LT) and Wassuk Range (WR) zones (Fig. 3D; Table 2) could suggest significant extension along the western margin of the Walker Lane at this latitude. The anomalously low average v_{ext} value of the Wassuk Range zone is caused primarily by the negative v_{ext} values for 4 sites within the zone (Fig. 3A and D; Table 1). Despite this low average value, the average v_{ext} values for the Wassuk Range (WR), Gabbs Valley Range (GVR), and Basin and Range (BR) zones are all within error, based on error ellipses (Oldow, 2003) and 2σ ellipses (USGS Earthquake Hazards Program, 2006) shown in Fig. 3A. If the true v_{ext} vectors of the Wassuk Range zone are similar to those within zones to the east (3–3.5 mm/yr), the ~2 mm/yr relative strain rate across the entire Walker Lane at this latitude might be entirely accommodated along the western margin of the Walker Lake domain. *T*-test analyses between v_{ext} populations involving the Wassuk Range zone are affected by an artifact of the v_{ext} calculation (i.e., v_{ext} becomes negative for stations where the v_{dex} vector is more northerly than N35°W), so are not used in determining statistical differences between most zones. However, t-test analysis of the Gabbs Valley Range and Basin and Range zones is not affected by this issue and demonstrates statistical similarity between v_{ext} populations (Table 3).

Thus, geodetic data show a partitioning of strain similar to that seen in the geologic record. Extensional strain of ~2 mm/yr or more might be focused in the western section of the Walker Lake domain, proximal to the Sierra Nevada range front, and dextral strain is focused in the eastern section of the domain. This dextral strain is largely localized across a very narrow zone of perhaps 15–20 km in the east that coincides with mapped dextral faults, with little dextral motion occurring to the west of this localization and a minor component of dextral deformation occurring to the east (Fig. 3; Table 2). These data do not show a constant westward increase in extensional and dextral velocities (Fig. 3).

4. Seismicity in the Walker Lake domain

The most significant concentrations of seismicity across the central Walker Lane at this latitude have been associated with either the Central Nevada seismic belt (CNSB) or faults proximal to the Lake Tahoe area (Fig. 5A; e.g., Rogers et al., 1991). In the western section of the Walker Lake domain, fault-slip indicators (e.g., Zoback, 1989; Surpless, 1999), well-preserved fault scarp morphology, and paleoseismic studies (e.g., Ramelli et al., 1999; Demsey, 1987) suggest that the Genoa fault and the range-bounding fault on the east flank of the Wassuk Range (Fig. 2A) are youthful, active normal faults with significant dip-slip displacements. However, neither normal fault displays significant historical seismicity (Fig. 5A). Further east, there is little seismic activity associated with the central and northwestern segments of most dextral faults of the Gillis and Gabbs Valley Ranges (Figs. 2A and 5A), where geodetic data indicate significant modern dextral strain (Fig. 3B).

Unraveling the complexities of ongoing fault processes utilizing seismic activity across the Walker Lake domain is difficult due to inherent limitations of seismic data including: 1) the relatively short timeframe represented by the earthquake record (~150 years) in the context of earthquake cycles that can span thousands of years; 2) the lack of focal mechanisms for older events due to lower quality of older data and the initially small number of seismic stations; and 3) the relatively uneven geographic distribution of seismic stations until the past several decades. However, the distribution and style of earthquake activity do reveal several important features about the complex pattern of faulting across the region.

4.1. Seismicity in the Western Section of the Walker Lake domain

The concentration of seismicity on the western margin of the Basin and Range province has long been recognized (e.g., Eaton, 1982; Eddington et al., 1987) and used as evidence of continued westward expansion of the province (e.g., Dilles and Gans, 1995; Surpless et al., 2002). Although the Lake Tahoe earthquake of 1977, the Virginia City earthquake of 1981, and the Border Town earthquake of 1995 all revealed motion compatible with dip-slip deformation of a normal fault (Fig. 5B; Ichinose et al., 1997, 1998), Schweickert et al. (2004) note that the most significant normal fault zone in the Lake Tahoe area, the Genoa fault, displays a very low rate of historic seismicity (Fig. 5A); the highest rates of seismic activity in the area occur in three clusters, named the Gardnerville, Carson, and Truckee transition zones (Fig. 5A; Schweickert et al., 2004).

The seismic events in these transition zones are characterized by low-magnitude slip on small, high angle, NNE- and NNW-striking conjugate strike-slip faults that poorly correspond with mapped surface faults (Ichinose et al., 1998; Schweickert et al., 2004). The seismicity of the Truckee transition zone extends outside of the Walker Lake domain to the north, so is not discussed here. The left-

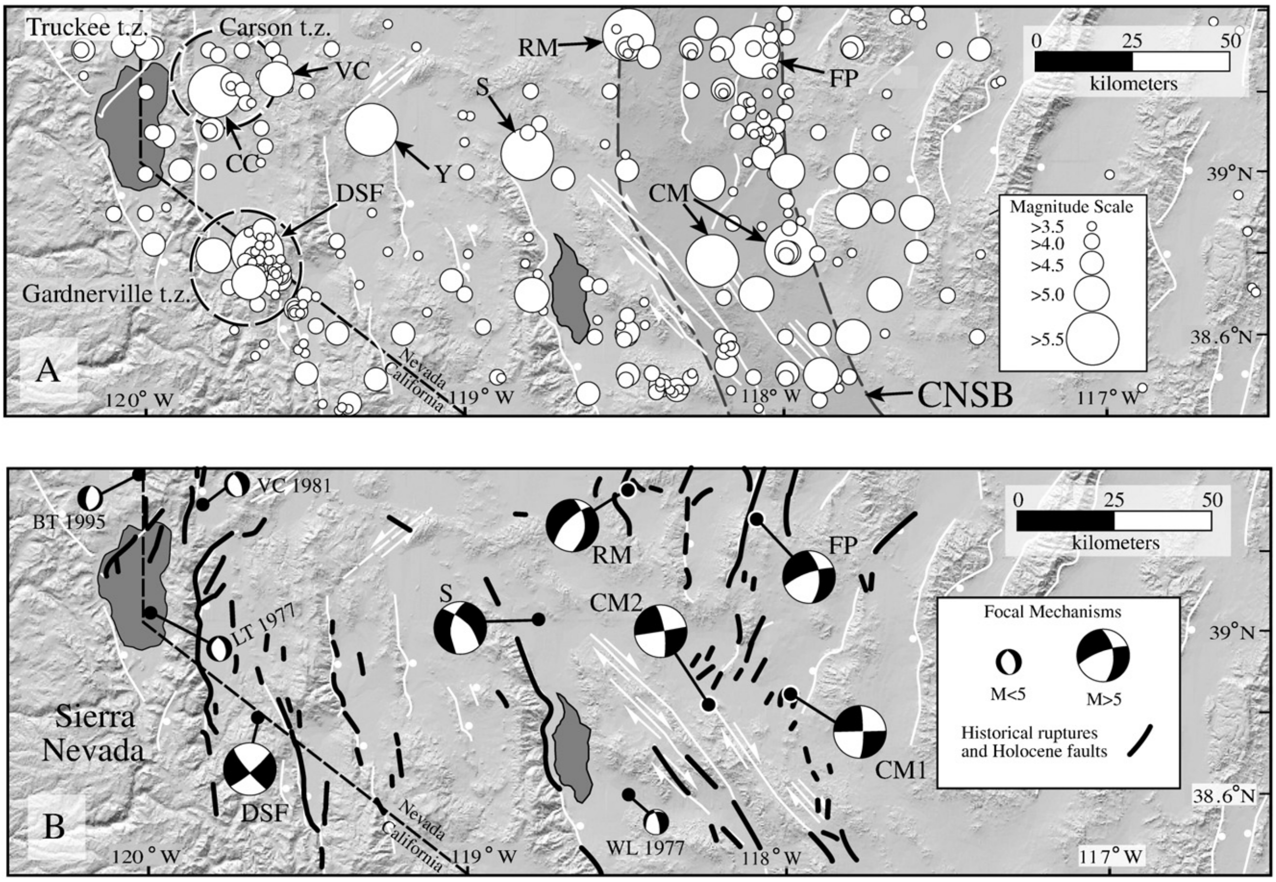

Fig. 5. A: Earthquakes of magnitude 3.5 and greater from the late 18th century to 2007 in the central Walker Lane region, based on the earthquake catalog of the University of Nevada, Reno Seismological Laboratory, Bell et al. (1999), and Doser (1986, 1988). The Carson and Gardnerville transition zones, as named by Schweickert et al. (2004) are circled, and the southern section of the Truckee transition zone is shown north of Lake Tahoe. The Central Nevada Seismic Belt (CNSB) is shaded (approximate boundaries from Rogers et al., 1991). Significant seismic events are abbreviated as follows: CC — 1860's Carson City earthquakes; CM — 1932–1933 Cedar Mountain EQs; DSF — 1994 Double Springs Flat EQ; FP — 1954 Fairview Peak EQ; RM — 1954 Rainbow Mountain EQ; S — 1959 Schurz EQ; VC — 1869 Virginia City EQ; and Y — 1933 Yerington/Wabuska EQ. B: Earthquake focal mechanisms and historical and Holocene fault ruptures. Locations of historical and Holocene fault ruptures from Bell et al. (1999) and United States Geological Survey and Nevada Bureau of Mines and Geology (2007). Focal mechanism data from Doser (1986, 1988), Ichinose et al. (1997, 1998), and Rogers et al. (1991 and the references therein). Focal mechanisms shown are from the largest earthquake event in each earthquake sequence. The abbreviations in B are the same as those used in A. For the earthquakes of magnitude less than 5, the events are abbreviated as follows: BT — Border Town; LT — Lake Tahoe; VC — Virginia City; and WL — Walker Lake.

stepping en echelon arrangement of the Genoa fault relative to the east-dipping normal fault system of the Sierra Nevadan range front, which extends further south (Fig. 5A), suggests that the position of the seismicity associated with the Gardnerville transition zone corresponds to an accommodation zone between two overlapping, synthetic major normal faults (e.g., Faulds and Varga, 1998). Similarly, the position of the Carson transition zone seismicity near the northern termination of the Genoa fault zone is near another left-step in the range front fault system (Fig. 5A). Analysis of historical seismicity and the geology of accommodation zones worldwide suggest that deformation in accommodation zones occurs along diffuse systems of small, discontinuous faults and fractures, as opposed to the rupture of long, relatively continuous strike-slip systems (Roberts and Jackson, 1991; Faulds and Varga, 1998). This description is consistent with observed data from the Gardnerville and Carson transition zones, but two hypotheses explain the cause of these concentrations of seismic activity located near the terminations of the Genoa normal fault.

Schweickert et al. (2004) suggest that these concentrations of historical seismicity are the result of a recent change in the broader stress field on the western margin of the central Walker Lane. Schweickert et al. (2004) hypothesize that the strike-slip faults defined by concentrations of seismicity and focal mechanism data (see Double Springs Flat event, Fig. 5) accommodate present-day north–south shortening (N–S oriented P axis), while the normal faults in the area accommodate east–west extension during different time periods (Schweickert et al., 2004). This spatial and temporal partitioning of strain (E–W extension and N–S shortening) could be related to two modes of seismic behavior that change depending on the orientation of maximum and minimum stress directions across the region (Schweickert et al., 2004).

Alternatively, the regional stress field may have remained relatively constant throughout the Holocene to the present. Earthquakes along major normal faults are often followed by concentrations of seismic activity, with a wide range in focal mechanisms, near the terminations of the faults (Roberts and Jackson, 1991; Faulds and Varga, 1998 and references therein). Pre-historic earthquake activity along the Genoa fault might have changed the local stress fields at the tips of the normal fault system, thereby initiating seismic activity in the Gardnerville and Carson transition zones. The diffuse concentration of seismicity in the Gardnerville transition zone is also consistent with the diffuse patterns of seismicity and faulting observed in accommodation zones elsewhere (Roberts and Jackson, 1991; Faulds and Varga, 1998). Moreover, the Genoa normal fault has remained active in the Holocene (Figs. 2A and 5B; e.g., Ramelli et al., 1999), so the seismicity of the Gardnerville transition zone may be related to a geologically-recent dip-slip earthquake along the main segment of the now-quiescent Genoa normal fault. Although accommodation zones are relatively low-risk regions for seismic hazard, significant earthquakes, such as the Double Springs Flat earthquake of 1996, do occasionally occur in these areas (e.g., Aki, 1979; King, 1983).

The two significant pre-historic earthquakes along the Genoa fault, with 3.0–5.5 m of dip-slip motion per event, suggest that despite a low level of historic seismicity, the Genoa fault remains active and has the potential to generate large magnitude (>7.0) earthquakes (Ramelli et al., 1999). Schweickert et al. (2004) hypothesize a period of relative seismic quiescence for the major normal faults of the Lake Tahoe region on the order of 1500 years or greater based on data presented by Ramelli et al. (1999), with the rate of accumulation of elastic strain controlled primarily by the large-scale motion of the relatively rigid Sierra Nevada–Great Valley microplate. Ichinose et al. (1998) suggest a different recurrence behavior for major normal faults of the Sierra Nevadan frontal system relative to the accommodation zones between the normal faults, with longer periods of quiescence between mainshock events along the normal faults, and shorter periods of quiescence between mainshock events along the strike-slip faults that link the larger structures. This hypothesis is consistent with observed patterns of seismicity, but cannot be evaluated because of the limited timeframe of the earthquake record and the lack of geologic or paleoseismic evidence for pre-historic earthquakes in either the Carson or Gardnerville transition zones.

Further east, the Pine Nut Mountains and the Singatse Range display very little historic seismicity (Figs. 2A and 5A), which might be due to significant accommodation of strain by folding instead of faulting in the area (Gilbert and Reynolds, 1973; VanWormer and Ryall, 1980). However, a significant 1933 earthquake of unknown displacement affected the area adjacent to Yerington (Fig. 5A; e.g., Rogers et al., 1991). Thus, despite no evidence for Holocene movement on the Singatse range front fault (Fig. 5B) and low levels of historic seismicity across both ranges, there is potential for significant earthquakes across the area (Fig. 5B). The lack of geologic or paleoseismic evidence for significant Holocene earthquakes across these ranges makes any evaluation of seismic hazard based on recurrence interval difficult.

Seismic activity present along the central Wassuk Range (Fig. 5A), combined with geologic evidence to the north and south, suggests continued dip-slip normal fault motion along most of the eastern flank of the range during Holocene time (Figs. 2A and 5B; e.g., Demsey, 1987; Surpless, 1999; Wesnousky, 2005b). The relative lack of seismicity along the northern part of the Wassuk Range, north of Bald Mountain (Figs. 2A and 5A), might be due to a long recurrence interval along that segment of the fault, as the last major dip-slip event in the northern Wassuk Range occurred at about 2.5 ka (Demsey, 1987; Wesnousky, 2005b). The gap in seismicity along the Wassuk Range frontal fault zone south of Walker Lake is coincident with the 10 kilometer segment of the fault that displays no evidence for Holocene movement (Fig. 5), and geomorphic evidence presented by Demsey et al. (1988) implies a less active southern range front fault system relative to the northern Wassuk Range.

The Schurz earthquake of 1959, the only significant historical seismic event near the Wassuk Range, displayed oblique normal–dextral fault motion (e.g., Rogers et al., 1991) and was located along strike of the dextral strike-slip faults to the southeast (Fig. 5), in a position close to the boundary between dextral-dominated and extension-dominated deformation proposed by Wesnousky (2005b). Small concentrations of seismicity are focused in the Garfield Hills and immediately north of the city of Hawthorne (Figs. 2A and 5B), but these clusters are not located along or adjacent to any significant mapped structures (VanWormer and Ryall, 1980), so are difficult to interpret or assess for seismic hazard.

Geologic evidence suggests that strain across the western section of the Walker Lake domain has been dominated by ~E–W extensional deformation accommodated by major normal faults with dip-slip motion since 15 Ma. Geodetic data presented here indicate a relatively low rate of extension across the entire central Walker Lane at present (2–4 mm/yr), which is consistent with the observed lack of seismicity on the normal faults that display the greatest Holocene displacements. However, geologic and paleoseismic data suggest that both the Genoa fault and the Wassuk range fault have been active in the Holocene and remain the most likely loci for major (M>7.0) earthquakes. In the case of the Genoa fault, this is supported by the concentrations of seismicity proximal to the terminations of the normal fault, which is in en echelon arrangement with the Sierra Nevadan frontal fault system to the north and south. Significant changes in the stress field on the western margin of the Walker Lane are not required to explain these clusters of seismicity.

4.2. Seismicity across the eastern section of the Walker Lake domain

Within the eastern section of the Walker Lake domain, seismicity is concentrated on the southern segments of the Indian Head, Gumdrop Hills, and Benton Springs faults (Figs. 2A and 5A) and along the eastern margin of the Walker Lane, proximal to and to the east of the Petrified Springs fault (Figs. 2A and 5A). Significant portions of all dextral faults in the domain display Holocene rupture (Fig. 5B) and modern dextral strain indicated by geodetic data (Fig. 3B; Tables 1 and 2) is localized across these faults, suggesting that dextral deformation will continue to occur. In addition, geodetic data indicate a localization of modern dextral strain accommodated proximal to the Petrified Springs fault, and GPS stations across the northern Gabbs Valley Range zone suggest no significant change in either dextral or extensional velocities (v_{dext} or v_{ext}) across the CNSB (Fig. 3).

However, the interpretation of seismic activity on the eastern margin of the Walker Lake domain is complicated by the seismic events of the Central Nevada seismic belt (CNSB), which extends to the north, outside the boundaries of the Walker Lane (Fig. 5A). Major events associated with the CNSB from the Walker Lake domain to areas to the north include the 1932 Cedar Mountain earthquakes, the 1954 Rainbow Mountain earthquake, the 1954 Fairview Peak earthquake (Fig. 5), the 1915 Pleasant Valley earthquake, and the 1954 Dixie Valley earthquake (epicenters to the north of the study area). Of these events, only the Cedar Mountain earthquakes took place within the boundaries of the Walker Lane.

Bell et al. (1999) constrain Quaternary dextral movement of the Cedar Mountain fault zone to a preferred rate of 0.4–0.5 mm/yr, based on paleoseismic data along the primary Cedar Mountain earthquake rupture zone, just to the east of the Benton Springs and Petrified Springs faults (Figs. 2A and 5A). Strike-slip motion within the Cedar Mountain rupture zone occurred along faults that strike more northerly than the well-established faults of the Walker Lake domain (Gianella and Callaghan, 1934; Caskey et al., 1996; Bell et al., 1999; Wesnousky, 2005b) but subparallel to existing mapped normal faults in the CNSB to the north.

The 1954 Rainbow Mountain and 1954 Fairview Peak earthquakes, produced normal–dextral oblique motion on east-dipping faults (Fig. 5; Doser, 1986), and further to the north in the CNSB, the 1954 Dixie Valley and 1915 Pleasant Valley earthquakes produced primarily normal, dip-slip fault motion along north to north–northeast striking fault planes (e.g., Doser, 1986; Rogers et al., 1991; Caskey et al., 1996). This transition from nearly pure strike-slip deformation within the eastern section of the Walker Lane to pure normal deformation in the northern CNSB might suggest that some component of dextral deformation documented in the Walker Lane to the south is presently transferred to steeply-dipping mapped normal faults of the central Basin and Range (e.g., Wesnousky, 2005b), with dextral motion decreasing with increasing distance from the Walker Lane. Based on extensive evaluation of faulting and seismicity in the CNSB, Rogers et al. (1991) suggest a mean recurrence interval for these recently active segments of 300–1500 years.

Thus, while geologic and geodetic evidence suggest significant dextral strain has been and will continue to be accommodated by faults in the Gabbs Valley and Gillis Ranges during Cenozoic time up to and including the Holocene, historic seismicity is virtually absent along the central and northern sections of mapped dextral strike-slip faults or in areas to the northwest (Figs. 1 and 5). Instead, seismic data indicate that most present-day earthquake activity is associated with the north-trending CNSB, with dextral motion occurring along faults that formerly accommodated dominantly dip-slip deformation (Figs. 1 and 2).

5. Discussion

Clear evidence suggests that transtensional strain is strongly partitioned across the Walker Lane, accommodated by low-magnitude E–W extension in the western part of the Walker Lake domain and plate-boundary parallel dextral motion in the east (Figs. 1, 2A, and 3; Table 2). This interpretation is supported by the integrated analysis of geodetic, seismic, and geologic data across the domain and differs from existing models that require either a localization of dextral strain along the Sierra Nevadan range front fault system (e.g., Unruh et al., 2003) or a broad distribution of both extensional and dextral motion across the entire Walker Lane at this latitude (e.g., Bennett et al., 1999; Flesch et al., 2000). These data permit tentative predictions regarding future local and regional deformation, and when combined with other studies, provide potential explanations for the strong partitioning of strain across the Walker Lake domain.

5.1. Future local and regional deformation

Geologic and geodetic data suggest that extension across the western zone of the Walker Lake domain is accommodated proximal to the Genoa fault, the present-day location of the Sierra Nevadan range front fault system at this latitude (Table 2; Figs. 2A and 3C). Although slip rate alone is not a reliable criterion for modeling seismic hazard in the western Basin and Range (Bell et al., 1999), the youthful fault scarp morphologies and evidence for recent, significant dip-slip earthquakes are strong evidence for the likelihood of renewed normal fault activity, especially along the Sierra Nevadan Range front fault system. Although slip rates are of lower magnitude along the eastern flank of the Wassuk Range, geologic data indicate active Holocene dip-slip motion and associated Holocene earthquake activity along the fault system (Demsey, 1987).

The lack of seismicity along the most active normal fault systems in the western section of the domain is consistent with both the evidence for a quiescent period following recent earthquakes and the relatively low present-day extensional strain rate across the western Walker Lane at this latitude (~2 mm/yr; Fig. 3C and Table 2). The most significant clusters of earthquakes in the western section are likely associated with the terminations of the Genoa normal fault system.

Although most present-day dextral motion in the Walker Lake domain is localized across a narrow (15–20 km wide) zone of mapped dextral faults (Table 2; Fig. 3B), the focus of dextral strain displays a relative paucity of significant historical seismicity. The only significant historical earthquakes in the eastern section of the Walker Lake domain have been associated with the Central Nevada seismic belt (CNSB), which trends north to areas outside the boundaries of the Walker Lane (Fig. 5A). Several hypotheses could resolve the apparent discrepancy between seismic and other data from the eastern Walker Lake domain:

Hypothesis 1. GPS data define only the present-day localization of strain. This locus will soon shift to another longitudinal position before significant differential motion and/or seismicity has occurred. As the location of this differential motion continues to shift, the net effect will be distributed dextral motion across a wider area.

Hypothesis 2. Fault-block rotations similar to those hypothesized in the Carson domain to the north are distributing strain across a wider area, negating the necessity for significant seismic events associated with this modern dextral strain along strike of existing faults to the southeast.

Hypothesis 3. GPS data define a long-lived localization of dextral motion which has been and will continue to be accommodated by aseismic slip. In some cases, geodetic and earthquake data suggest that displacement accommodated by seismic activity is less than the accumulated regional motion, requiring displacement to be accommodated elsewhere (e.g., the San Andreas fault system). In other cases, this difference may be related to aseismic slip on a fault, and hence there will be no near-future earthquake activity associated with that fault (e.g., Stein and Wysession, 2003).

Hypothesis 4. GPS data have been strongly influenced by post-seismic effects of major earthquakes of the Central Nevada seismic belt (CNSB).

Hypothesis 5. The CNSB is now accommodating dextral strain previously accommodated by the Walker Lane. Although the geology of the region suggests dextral faulting in the eastern section of the Walker Lake domain has been an important locus for accommodation of shear through the Holocene, historical seismicity suggests the CNSB has become the focus of dextral strain associated with plate-boundary parallel motion.

Hypothesis 6. GPS data define the short-term elastic loading of the crust, while the mapped northwest-striking dextral faults represent the long-term plastic accommodation of strain. The lack of seismicity across the eastern zone is the expected result of the pattern of seismic activity associated with earthquake cycles.

Although the position of maximum strain may change over time in some fault systems (e.g., Wallace, 1984), the geologic record supports a long-term (>24 Ma) focus of dextral deformation in the Gillis and Gabbs Valley ranges of the Walker Lane, eliminating the hypothesis that significant temporal longitudinal shifts in the position of greatest right-lateral motion have occurred and will continue to occur in this region (Hypothesis 1). In addition, presently active fault-block rotations would require a relatively constant change in GPS dextral velocities over a range of longitudes, which is not observed in the velocity data (Fig. 3); the data instead show a very localized accommodation of dextral strain. Also, no geologic evidence supports significant rotation of fault blocks about vertical axes in the Walker Lake domain, eliminating the fault-block rotation hypothesis from consideration (Hypothesis 2).

The occurrence of significant historic earthquakes in regions south and east of the focus of present-day dextral motion defined by geodetic data and the relative homogeneity of the geology of the region makes it unlikely that aseismic slip is accommodating a significant component of this motion (Hypothesis 3). In fact, there is no documented case of aseismic creep on faults in the Basin and Range (Hammond and Thatcher, 2007).

Dixon et al. (2003) found that earthquake-cycle effects and the viscoelastic rheology of the lower crust and upper mantle can affect slip rate estimates determined from geodetic data. Their analysis provides an explanation for discrepancies between geodetic and geologic estimates of fault-slip rates. Wernicke et al. (2000) suggested that velocity values associated with post-seismic relaxation were on the same order as the background signal for most of the Basin and Range. However, Hetland and Hager (2003) used a viscoelastic post-seismic relaxation model of the four largest historic earthquakes of the CNSB and found that 60–70 years after the 1932 Cedar Mountain earthquakes (the approximate period over which GPS data analyzed in this paper were collected), the velocities attributed to that event account for less than 1 mm/yr shear in the area proximal to the fault system (Fig. 4B in Hetland and Hager, 2003). In addition, although Hammond et al. (in press) suggest that between 25 and 50% of the shear strain between longitudes 117° and 118.5° can be explained by transient, post-seismic deformation, their model's strain field has a spatial wavelength on the order of hundreds of kilometers, so doesn't produce significant variation in a single site relative to geodetic stations tens of kilometers away. These data indicate that post-seismic effects from the last major earthquake in the area do not have an appreciable effect on the localization of dextral strain delineated by geodetic data (Hypothesis 4).

Based on her analyses of earthquakes of the CNSB, Doser (1988) suggested that the Walker Lane does not represent an active tectonic boundary. The similarity in both the rupture processes and the *P* and *T* axes of focal mechanisms from the Cedar Mountain earthquake sequence and earthquakes further north in the CNSB might indicate that the CNSB should be considered the active intraplate boundary (Doser, 1988). Hetland and Hager (2003) evaluated the geodetic data from an area that includes the CNSB and discovered that very little strain is accumulated across the CNSB, after removing the preferred models of post-seismic relaxation from geodetic velocities. West of the CNSB, modern shear strain increases approaching the Sierra Nevada range front (Hetland and Hager, 2003), consistent with models that suggest the Sierra Nevadan crustal block is moving to the NNW (e.g., Dixon et al., 2000), with shear strain associated with plate-boundary parallel motion accommodated proximal to the central and northern Walker Lane. Although these studies do not eliminate the CNSB as an important structural feature in the central and northern Basin and Range, the consistent pattern of deformation and strain recorded by geologic and geodetic data seems to suggest that the Walker Lane remains the more important intraplate feature.

In addition, geodetic data presented here suggest that the localization of dextral strain in the Walker Lake domain is not coincident with the CNSB (Figs. 3B and 5A); in fact, geodetic data from the Gabbs Valley Range zone show no appreciable change in dextral strain across the entire CNSB (Figs. 3B and 5A). While seismic data do indicate that the CNSB is an active feature, geologic and geodetic data indicate that most past strain across the CNSB has been dominated by extension (dip-slip normal faults), with the only significant structural features accommodating dextral deformation present along the Walker Lane, further weakening the CNSB hypothesis (Hypothesis 5).

It is difficult to infer ongoing seismic slip from historical seismicity, due primarily to the relatively short time period for which data are available (e.g., Stein and Wysession, 2003). However, the localization of dextral strain across such a narrow region in the eastern section of the Walker Lake domain might signal a significant, ongoing elastic loading process. Although not all of the strain recorded by geodetic means will necessarily be released in a future earthquake (e.g., Norabuena et al., 1998; Stein and Wysession, 2003), if even a fraction of the ~3–5 mm/yr dextral shear strain is accommodated by future slip along dextral faults, this strain localization becomes significant. The lack of seismicity associated with the region is an expected part of the earthquake cycle, but the lack of paleoseismic data across the central and northern portions of these faults prevents estimation of earthquake recurrence interval for either individual faults or for the system as a whole. If the localization of dextral strain delineated by geodetic data is a long-term phenomenon, as geologic data suggest, future seismic activity in presently-quiescent areas should be expected (Hypothesis 6).

5.2. Crustal strength and the initiation of strain partitioning

The dextral shear observed along the Walker Lane is thought to be caused primarily by shear stress applied to the margin of California by Pacific–North American plate interactions, while extensional deformation in the same region is considered primarily a consequence of the large gravitational potential energies of the western U.S. (e.g., Humphreys and Coblentz, 2007). In the central Walker Lane, where both dextral shear and extension are observed, it is clear that both plate boundary and intraplate influences have helped shaped the region's landscape. However, the initiation of long-term strain partitioning requires further explanation.

Although the mapped dextral faults of the eastern Walker Lake domain were active as early as 24 Ma (Ekren et al., 1980; Ekren and Byers, 1984; John, 1992), most fault motion has taken place since 15–10 Ma (e.g., Hardyman and Oldow, 1991; Oldow et al., 1994), which coincides with the onset and migration of extensional deformation of the western Walker Lake domain (Dilles and Gans, 1995; Henry and Perkins, 2001; Surpless et al., 2002; Schweickert et al., 2004). To explain the synchronous extensional and dextral fault motion in close proximity, Ichinose et al. (1998) hypothesize a gravitational collapse of the eastern central Sierra Nevadan block caused by the initiation of the Walker Lane dextral shear system. This hypothesis is consistent with a proposed magmatically-induced thermal weakening of the crust prior to the onset of significant normal faulting across the western zone of the Walker Lake domain in Miocene time (Surpless et al., 2002), which would aid the gravitational collapse and the initiation of extension. While these studies help explain the initiation of strain partitioning in the Walker Lake domain, Hammond and Thatcher (2004) suggest that a rheologically weak lithosphere beneath the Walker Lane continues to permit the concentration of shear and extensional deformation in close proximity.

5.3. Stress–strain relationships and long-term strain partitioning

In the central Walker Lane, it appears that modern wrench simple shear is currently taken up along relatively long-lived dextral strike-slip faults in the eastern Walker Lake domain while a residual component of dip-slip extension is accommodated along the N–S striking dip-slip faults of the western domain. This rapid spatial transition in fault orientation and slip direction is too abrupt to be associated with a similar spatial change in the stress state. Using the Carboniferous Northumberland basin of the United Kingdom as an example, De Paola et al. (2005) demonstrate that in oblique extensional settings, fault localization and slip direction are strongly influenced by pre-existing basement structure, so that components of wrench simple shear could be taken up along pre-existing planar structures or within narrow zones, leaving residual dip-slip extensional components to be accommodated within adjacent domains. These findings are consistent with hypothesized pre-Cenozoic crustal structural control of the partitioning and localization of strain observed in the central Walker Lane (e.g., Wetterauer, 1977; Cogbill, 1979; Oldow et al., 1994).

However, the present-day least principal stress direction (σ_3) is oriented approximately N70°W across the western margin of the Basin and Range at this latitude (Humphreys and Coblentz, 2007), which seems incompatible with the orientation of both extensional and dextral strain suggested by both geologic and geodetic evidence. Further, Kreemer and Hammond (2007) hypothesize that extension directions in the Basin and Range have rotated through time in response to the northward migration of the Mendicino triple junction, so the long-lived partitioning of strain documented across the Walker Lake domain has occurred in a rotating stress field with no evidence for any significant change in slip direction accommodated by either the eastern or western Walker Lake domains. The relatively static nature of the partitioning of types of strain in the context of a rotating regional stress field might be explained by relatively low stress ratios in the region.

Based on 3D modeling of fault systems, Scotti and Nur (1990) suggest that at low stress ratios (σ_2 of similar magnitude to σ_3), faults in adjacent domains (as defined by fault orientation) can display contrasting slip directions at the same point in time. In addition, the angular relationship between principal stress directions and fault orientations can change significantly and continue to permit motion along the fault without requiring the initiation of new faults in response to changes in the stress field–fault plane relationship (e.g., Scotti and Nur, 1990).

In the central Walker Lane, the western Walker Lake domain and the eastern Walker Lake domain display contrasting fault orientations and slip directions, consistent with low stress ratios, and fault motion has continued on systems in both domains throughout regional stress field rotation. Therefore, it is likely that fault orientations and accommodation of strain across the central Walker Lane are controlled by a combination of pre-Cenozoic crustal structure, a relatively weak lithosphere beneath the Walker Lane, and long-term low stress ratios in the crust.

5.4. Tectonic implications

Previous studies show that ongoing dextral strain across the central and southern Walker Lane is significantly greater than dextral strain across the northern Walker Lane (e.g., Thatcher et al., 1999; Oldow, 2001; Wesnousky, 2005b), suggesting that there is a significant change in the accommodation of strain north of the Walker Lake domain. Hetland and Hager (2003) suggest that dextral strain is similar to the north but distributed across a much wider zone that includes areas to the east of the boundary of the northern Walker Lane. If true, then the boundaries of the northern Walker Lane may not encompass all areas of the western margin of the Basin and Range province undergoing intraplate dextral shear.

The complexity of faults throughout the Walker Lane, relative to the San Andreas fault system, might be in part controlled by the lower cumulative dextral slip accommodated by the Walker Lane (e.g., Wesnousky, 2005a). Laboratory studies by Wilcox et al. (1973) suggest that a zone of discrete fault segments taking up displacement will later become a single, through-going fault as the system matures. The geographical distribution of dextral faults along the central (Walker Lake domain) and northern (Pyramid Lake domain) portions of the Walker Lane (Fig. 1) and the lower total strain accumulation (relative to the San Andreas fault system) suggest a relatively young fault system; these now geographically distinct sets of dextral faults may become a continuous, large-scale system as strain continues to accumulate (Faulds et al., 2005). In the case of the dextral faults in the eastern zone of the Walker Lake domain, the present-day rates of strain suggest future seismic activity of one or more faults in the mapped dextral system. As slip accumulates across these faults, the overall length of the fault system should grow to the north, potentially connecting with the dextral faults in the Pyramid Lake domain.

Faulds et al. (2005) suggest that the Walker Lane has grown toward the northwest in Miocene time, possibly due to increasing contact between the Pacific and North American plates (Atwater and Stock, 1998). Cashman and Fontaine (2000) show that large-scale clockwise block rotations have been accommodated by a series of NE-striking sinistral faults in the Carson domain (Fig. 1). These block rotations (Cashman and Fontaine, 2000) are consistent with dextral deformation in the Carson Sink area to the east, where the gap in mapped strike-slip faults exists, supporting Faulds et al. (2005) hypothesis that a semi-continuous zone of localized dextral deformation has developed since Miocene time.

6. Conclusions

The clear partitioning of extensional and dextral deformation across the Walker Lake domain indicated by both geologic and geodetic data suggests that the central Walker Lane cannot be treated as a broad zone of transtension in tectonic models. If the rates of extensional strain indicated by geodetic data continue across the western zone of the Walker Lake domain, and if the narrow localization of dextral strain continues in the eastern zone of the Walker Lake domain, both areas could become loci for significant future earthquakes, despite a paucity of historic seismicity. This partitioning of strain across the Walker Lake domain is likely controlled by a combination of pre-Cenozoic crustal structure, a rheologically weak lithosphere, and low stress ratios, permitting contrasting modes of deformation to occur in close proximity from Miocene time to the present. Moreover, the apparent localization of dextral deformation along the central and northern Walker Lane and the inland-stepping history of the San Andreas system (Atwater and Stock, 1998) allow the possibility that the Walker Lane will become increasingly important to North American–Pacific plate boundary dynamics (Faulds et al., 2005). The now discrete, discontinuous systems of dextral faults in the Pyramid Lake and Walker Lake domains may one day become a continuous, major fault system, accommodating an increasing percentage of the overall relative plate motions.

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