cene (9) shows that no equilibrium in the carbon cycle is established and that the waxing and waning of the terrestrial biosphere, possibly related to subtle climate variations and early human land use, are the most important factors controlling atmospheric CO₂ concentrations over the last 10,000 years.

During further glaciation in MIS 5.4, CO₂ concentrations remain constant, although temperatures strongly decline. We suggest that this reflects the combination of the increased oceanic uptake of CO₂ expected for colder climate conditions and CO₂ release during MIS 5.4 (12). In any case, about 5°C balance the CO₂ uptake by the ocean.

Recent anthropogenic warming.

The northern Basin and Range province is an actively deforming intracratonic plateau lying between the stable blocks of the Sierra Nevada and the Colorado Plateau (Fig. 1).

The province has extended (increased in area) by about a factor of 2 over the past ~20 million years (1, 2), and extension continues with ongoing seismic activity and slip along numerous faults distributed across a zone ~800 km wide (3–5). Constraints on the internal deformation of the province are limited. Geologic studies delineate regions of Holocene and late Quaternary fault slip (3, 4).

Space geodetic measurements broadly define movements across the province (6–8), and
local surveys map concentrated deformation in several seismically active zones (9–11). The detailed pattern is important because it defines the current seismic hazard, with regions of high velocity gradient having more frequent damaging earthquakes than regions of low gradient. In addition, the spatial pattern constrains the fundamental processes driving active continental deformation, suggesting that external plate motions are more important than internal buoyancy forces in deforming the province.

Here we show the detailed velocity field mapped from a dense Global Positioning System (GPS) network that spans the Basin and Range. The GPS network consists of 63 stations, most of which were occupied on 2 or more days during surveys in 1992, 1996, and 1998 (12). The velocity of each station relative to stable North America was determined (Fig. 1), and velocity magnitude and vector orientations were calculated (Fig. 2).

Several first-order features are immediately apparent from Figs. 1 and 2. First, deformation is strongly concentrated in two regions: the westernmost ~200 km and easternmost ~100 km of the network, with little internal deformation of the intervening ~500 km of the central Basin and Range. Locally high velocity gradients (Fig. 2A) are associated with fault zones near 111.8° (Wasatch fault), 113° (Drum Mountain fault), 117.9° (Central Nevada seismic zone (CNSZ)), and across a more diffuse zone of conjugate strike-slip and normal faults between 119.1° and 120.2° (Sierra Nevada transition zone (SNTZ)). This pattern is broadly consistent with existing geologic, seismic, and space geodetic data. Reconnaissance geologic mapping (3, 4) and seismicity compilations (5) show evidence for Holocene fault slip and historical seismic activity in central Utah and western Nevada but for pre-Holocene slip.

Fig. 1. GPS station velocities relative to other stations on the stable North American plate lying to the east of the network shown here. One standard deviation error ellipses are shown for each vector (27). The base map is shaded topography derived from data from the U.S. Geological Survey digital elevation model. State boundaries (CA, California; NV, Nevada; UT, Utah; AZ, Arizona) and stable blocks of the Sierra Nevada and Colorado Plateau are shown for reference. Active faults (3, 4) are shown by solid green lines. The velocities of four stations on the stable Sierra Nevada block are shown with blue arrows. Velocities of Basin and Range stations are shown with red arrows.

Fig. 2. Velocity magnitude (A) and azimuth measured clockwise from north (B) plotted versus longitude. Only the GPS stations along U.S. Highway 50 shown in Fig. 1 are plotted. However, the velocities of four additional continuously recording GPS stations (open circles) that lie within the stable Sierra Nevada block are shown for comparison. Error bars indicate 1 SD. Major range-bounding faults with Holocene slip (long-dashed lines) and Quaternary slip (short-dashed lines) are shown in (A), and the 308° azimuth of North America–Sierra Nevada relative motion (13) is shown by the horizontal dashed line in (B).
and low seismicity levels in the central Basin and Range. Widely spaced VLBI (Very Long Baseline Interferometry) and continuous GPS station data are consistent with our results (13).

The distribution of deformation across western Nevada suggests that the 8 to 12 mm/year of \( \approx 310^\circ \)-oriented relative motion across the eastern California shear zone (7, 14–16), which lies south of our network near longitude 118°W, is partitioned between two fault zones. Average velocities of 2.8 \( \pm \) 0.5 mm/year between 114.9° and 117.7°W increase to 6.5 \( \pm \) 0.7 mm/year between 118° and 119.2°W and to 12.5 \( \pm \) 1.5 mm/year between 119.9° and 120.2°W. Thus, 2.8 \( \pm \) 0.5 mm/year of relative motion occurs across the Wasatch and related faults in central Utah, 3.7 \( \pm \) 0.8 mm/year of relative northwestern motion occurs across the CNSZ, and an additional 6.0 \( \pm \) 1.6 mm/year is accommodated within the SNTZ. The latter value is within the range of the \( \approx 3 \) to 6 mm/year of 300°-oriented motion inferred across faults in northwestern California and central Oregon (17), which suggests that much of this deformation may be accommodated through western Nevada.

Velocity vectors within the Basin and Range show the superposed effects of extensional stresses due to lateral density gradients in the lithosphere and tractions exerted by the relative motions of the bounding stable blocks. The average trend in velocity vector orientations across the province (Fig. 2B) is close to 310°, which is the direction of relative motion of the Sierra Nevada microplate with respect to stable North America (6, 7, 13), immediately suggesting the influence of this motion on internal deformation of the province. However, local variations in vector orientations provide clues that internal driving forces also affect the deformation.

The \( \approx 295^\circ \) orientation of velocities in central Utah would seem to suggest deformation due largely to the motion of the Colorado Plateau (essentially stable North America) relative to the eastern Great Basin. However, the \( \approx 1 \)-km increase in elevation and 15-km increase in crustal thickness across the Basin-Range/Colorado Plateau transition zone is expected to produce extensional stresses perpendicular to the Wasatch fault zone in central Utah (18). Geodetic measurements across the Wasatch zone are consistent with this stress field orientation. Velocity vectors and extensional strains are nearly normal to the local N20°E trends of the faults across our network (Fig. 1) and to the north-south–striking Wasatch zone near Ogden, 200 km farther north (9, 10). These orientations are also consistent with least principal stress orientations inferred from various stress indicators near the Wasatch front (19).

Between 118° and 120°W, the orientation of velocities is within \( \pm 15^\circ \) of the vector defining the relative motion of the Sierra Nevada block with respect to stable North America. This orientation, along with the high-velocity gradients across the region, suggest that Pacific plate–coupled motion of the Sierra Nevada microplate is responsible for much of the deformation of western Nevada. However, the large component of normal faulting present in this region suggests the perturbing influence of extensional stresses caused by buoyant, low-density, upper mantle beneath the Great Basin (20, 21). The local 295° orientation of velocity vectors across the Sierra Nevada–bound Genoa fault, a pure dip-slip north-south–striking normal fault near 120°W, may be due to the perturbing effects of stresses generated by topographic gradients across this transition zone (18). These stresses would tend to rotate velocity vectors toward the normal to the Genoa fault in the elevated Sierra Nevada and away from this direction in the lower lying Basin and Range, as observed.

The velocity field measured across active faults provides estimates of fault slip rate and constraints on the mechanism of elastic strain buildup in the adjacent crustal blocks (22). An elastic half-space dislocation model with a normal fault dipping 60° that does not slip between the surface and some fixed depth (H) but slides freely at a constant slip velocity below that depth yields the horizontal velocity expected due to elastic strain accumulation across the fault (23) (Fig. 3). The locked zone depth is taken to be the depth to which seismic fault slip or small earthquake hypocenters extend, which is 10 to 20 km in the Basin and Range. The high-velocity gradient in the model is \( \approx 3 H \) wide, or 30 to 60 km for locking depths that are appropriate here. For the area covered by our network, the expected pattern of horizontal velocity across an individual fault is thus well represented by a smoothed step and local peak or trough, with the net offset equal to the horizontal component of the fault slip rate. Strain accumulation across a series of widely spaced faults should resemble an irregular staircase, with steps being the zones of elastic strain accumulation and flats representing the intervening undeformed blocks.

The observed pattern of deformation across most of Nevada is similar to these expectations, with high-velocity gradients near 118° and 119.6°W and nearly constant velocities elsewhere. Figure 4 shows that bur-

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**Fig. 3. (A)** Horizontal velocity (west motion positive) versus distance for a fault model like that used in Fig. 4 to match velocity patterns across faults in Nevada. Horizontal distance is in kilometers perpendicular to the surface projection of a two-dimensional, 60°, west-dipping normal fault. The vertical axis gives the horizontal velocity component perpendicular to the fault normalized by the slip rate on the fault. **(B)** Model fault geometry.

**Fig. 4. (A)** Observed velocities (circles as in Fig. 2A with 1-SD error bars) compared with the model calculation (solid curve) plotted versus longitude. The model includes two 60° dipping faults. One is inclined to the west beneath the CNSZ and slips at 8 mm/year. The other dips to the east beneath the SNTZ and slips at 12 mm/year. **(B)** Model fault geometry.
ied faults beneath the CNSZ and SNTZ can explain the main features of the data. Both normal and right-lateral strike-slip faulting occur across each zone, so the modeled fault slip rate is the resultant of these two components. Because a number of active faults are exposed at the surface in each zone, the models are undoubtedly oversimplified. For example, the SNTZ contains both strike- and dip-slip faults, and the width of the deforming zone suggests that several subparallel faults locked to ~10 to 15 km would match the data at least as well as a single fault locked to 30 km.

Movements in central Utah and eastern Nevada are more complex than those shown by the simple buried fault slip model. Horizontal velocities (Fig. 2A) increase near the Wasatch fault zone as expected but then abruptly decrease west of it. Velocity subsequently increases near the Drum Mountain faults, decreases to the west, and finally reaches a stable value of ~3 mm/year west of 113.3°W. There is suggestive evidence that a local velocity decrease similar to those shown in central Utah occurs near the Schell Creek Range [at 114.6° (Fig. 2A)]. The changes there are small, about 2 mm/year, and are supported by very few observations. However, it may be noteworthy that this is the only mapped Holocene fault that crosses our network and roughly centered on 40°N show an increase in velocity west of the central Nevada seismic zone, which is consistent with our data. An inferred linear east-to-west increase of the component of velocity (8) is not supported by our data. Instead, our data show an abrupt increase of east and north velocity components near 118°W.

18. Isotopically balanced lateral differences in topography result from lateral plate motions that generate horizontal forces capable of causing deformation. For a two-dimensional structure across which the difference in topographic elevation is h and isotopic compensation occurs entirely within the crust, the force per unit length, F, normal to the structure is given by

\[ F = \rho_p g (h + \rho_m g / \rho_c) - \rho_c \rho_m \]

where \( \rho_p \) is crustal density, \( \rho_m \) is mantle density, \( g \) is the gravitational acceleration, and \( h + \rho_m g / \rho_c \) is the crustal thickness of the low-lying region. The magnitude of these forces will differ if horizontal density contrasts extend into the mantle. For example, the driving force will be smaller than computed above if the mantle lithosphere is colder and denser beneath the Sierra Nevada and Colorado Plateau than it is beneath the Basin and Range.

19. We assume that principal stress orientations estimated from earthquake fault plane solutions, borehole elongations, and slip directions on faults are coincident with incremental principal strains determined by GPS. M. L. Zoback [J. Geophys. Res. 94, 7105 (1989)] has estimated least principal stress orientations that are nearly east-west across the Wasatch fault near Ogden and N90°E to N120°E across our GPS network.
21. C. H. Jones, J. R. Unruh, and L. J. Sonder [Nature 381, 37 (1990)] calculate that the driving force contribution of buoyant upper mantle in the northern Basin and Range (termed gravitational potential energy by them) averages 1.5 \times 10^{-14} \text{N m}^3, which is comparable to the effects of province margin topography given in (18). However, these authors also point out significant uncertainties in the GPS derived force gradients due to poor constraints on the exact upper mantle density structure and its lateral variations.
23. L. B. Freund and D. M. Barnett, Bull. Seismol. Soc. Am. 66, 667 (1976). The horizontal displacement pattern in Fig. 3 is for a west-dipping fault. If the fault has an eastward dip, the pattern is reversed, with all local peaks replaced by troughs and vice versa (turn Fig. 3 upside down to visualize this). For dips shallower than 60°, the local peaks and troughs become progressively less prominent for the same slip distribution as that in Fig. 3.
24. The central Utah models use two 60° dipping faults locked from the surface to a depth of 15 km. Slip of 4 mm/year required across the Wasen fault and 2 mm/year across the Drum Mountain fault. These slip rates are surprisingly high and may be related to a discrepancy noted by others in the Ogden, where geologically estimated late Holocene slip rates are 1 to 2 mm/year [D. P. Schwartz and K. J. Coppersmith, J. Geophys. Res. 89, 5681 (1984)] and geodetic estimates are ~5 mm/year (9, 10).
25. Some of the local velocity changes near fault crossings of our network may be due to a sampling bias. Both coseismic slip fault and topographic height
Brown dwarfs (BDs) are “failed stars”; that is, they are not massive enough to sustain stable hydrogen burning but are sufficiently massive to start deuterium burning (1). Brown dwarfs are more like giant planets than stars in that their luminosity and temperature drop continuously with time, and ultimately they become extremely cool and faint. The borderline between stars and BDs is estimated to be at about 0.075 solar mass ($M_\odot$) (2). Of less importance is the temperature at which deuterium burning begins, which is around 4.2 million Kelvin ($K_\odot$). With $M_\odot$ decreasing, the temperature at which deuterium begins to burn decreases and eventually disappears. On the other hand, in very low-mass stars, the temperature and pressure at the core drop continuously with time, and the star becomes red. The deuterium burning object is resolved into two components of nearly equal brightness with a projected separation of 0.275 arc second (5 astronomical units for a distance of 18 parsecs). This binary system will be able to provide the first dynamical measurement of the masses of two brown dwarfs in only a few years. Upper limits to the mass of any unseen companion in Kelu 1 yield a planet of 7 Jupiter masses aged 0.5 × 10^{9} years, which would have been detected at a separation larger than about 4 astronomical units. This example demonstrates that giant planets could be detected by direct imaging if they exist in Jupiter-like orbits around nearby young brown dwarfs.

The first free-floating BD discovered in the solar neighborhood was Kelu 1. It was found in a proper motion survey (9). The second nearby free-floating BD was discovered by the Deep Near-Infrared Survey (DENIS). The DENIS and 2MASS surveys are ongoing and have the aim of yielding a complete sky coverage in the near-infrared I, J, and K’ bands (10). The analysis of only 220 square degrees (about 1% of the planned systematic errors can be up to 0.1 magnitude. We obtained a separation of 0.275 ± 0.002 arc sec and a position angle of 41.0 ± 0.2°. The apparent F110M, F145M, and F165M magnitudes (respectively) on the HST-Vega system are as follows: DENIS 1228-15 A (15.69, 14.96, and 13.98); DENIS 1228-15 B (15.89, 15.12, and 14.13); and Kelu 1 (14.13, 13.23, and 12.37). The standard deviation of these magnitudes is less than 0.01 magnitude, but the systematic errors can be up to 0.1 magnitude. Our F165M magnitude of 12.37 for Kelu 1 is in agreement with the published H magnitude of 12.32 (9). The B/A flux ratio of the DENIS 1228-15 system increases toward longer wavelength (0.83 for F110M, 0.86 for F145M, and 0.87 for F165M), indicating that DENIS 1228-15 B is slightly cooler than DENIS 1228-15 A. An independent confirmation of the binary nature of DENIS 1228-15 comes from public HST/NIC3 observations with filter F187N obtained on 24 June 1998 for another program by Hugh Jones and Todd Henry. The scale of NIC3 of 0.2 arcsec/pixel undersamples the PSF (theoretical full width at half maximum of 0.16 arc sec at 1.87 mm). Within the uncertainties due to the undersampling, the fitted values for the NIC3 data are in agreement with the results derived from the NIC1 data. The trigonometric parallaxes of DENIS 1228-15 and Kelu 1 are not yet known, although they can be obtained with ground-based telescopes (16). The distance to Kelu 1

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**A Search for Companions to Nearby Brown Dwarfs: The Binary DENIS-P J1228.2-1547**

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Hubble Space Telescope imaging observations of two nearby brown dwarfs, DENIS-P J1228.2-1547 and Kelu 1, made with the near-infrared camera and multiobject spectrometer (NICMOS), show that the DENIS object is resolved into two components of nearly equal brightness with a projected separation of 0.275 arc second ($5$ astronomical units for a distance of 18 parsecs). This binary system will be able to provide the first dynamical measurement of the masses of two brown dwarfs in only a few years. Upper limits to the mass of any unseen companion in Kelu 1 yield a planet of 7 Jupiter masses aged 0.5 × 10^{9} years, which would have been detected at a separation larger than about 4 astronomical units. This example demonstrates that giant planets could be detected by direct imaging if they exist in Jupiter-like orbits around nearby young brown dwarfs.