colder climate conditions and CO$_2$ release during the full interglacial CO$_2$ forcing encountered during MIS 5.4 (lower temperatures on the Antarctic ice sheet balance the CO$_2$ uptake by the ocean).

During further glaciation in MIS 5.4, CO$_2$ concentrations remain constant, although temperatures strongly decline. We suggest that this reflects the combination of the increased oceanic uptake of CO$_2$ expected for colder climate conditions and CO$_2$ release caused by the net decline of the terrestrial biosphere during the glaciation and possibly by respiration of organic carbon deposited on increasingly exposed shelf areas. These processes, however, should terminate (with some delay) after the lowest temperatures are reached in MIS 5.4 and ice volume is at its maximum at 111 ky B.P. (22). In agreement with this hypothesis, CO$_2$ concentrations start to decrease in the Vostok record at about 111 ky B.P. Another possibility to explain this delayed response of CO$_2$ to the cooling during MIS 5.4 would be an inhibited uptake of CO$_2$ by the ocean. In any case, about 5°C lower temperatures on the Antarctic ice sheet during MIS 5.4 (17) are difficult to reconcile with the full interglacial CO$_2$ forcing encountered at the beginning of this cold period and again question the straightforward application of the past CO$_2$-climate relation to the recent anthropogenic warming.

Another scenario is encountered during MIS 7, in which no prolonged warm period is observed. Although temperatures at the end of termination III are comparable to those at the end of termination II and CO$_2$ concentrations are even slightly higher, a much shorter lag in the decrease of CO$_2$ relative to the Antarctic temperature decrease in MIS 7.4 is found. Comparison with the SPECMAP record (23) shows that during the preceding interglacial MIS 7.5, ice volume was much larger than during the Holocene and the Eemian warm periods. Accordingly, the buildup of the terrestrial biosphere during MIS 7.5 is expected to be much less and sea level changes smaller, leading to a smaller net release of CO$_2$ into the atmosphere during the following glaciation, which is not able to fully counterbalance the CO$_2$ uptake by the ocean.

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Present-Day Deformation Across the Basin and Range Province, Western United States
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The distribution of deformation within the Basin and Range province was determined from 1992, 1996, and 1998 surveys of a dense, 800-kilometer-aperture, Global Positioning System network. Internal deformation generally follows the pattern of Holocene fault distribution and is concentrated near the western extremity of the province, with lesser amounts focused near the eastern boundary. Little net deformation occurs across the central 500 kilometers of the network in western Utah and eastern Nevada. Concentration of deformation adjacent to the rigid Sierra Nevada block indicates that external plate-driving forces play an important role in driving deformation, modulating the extensional stress field generated by internal buoyancy forces that are due to lateral density gradients and topography near the province boundaries.

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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.

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**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 ~310°-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 ± 0.5 mm/year between 114.9° and 117.7°W increase to 6.5 ± 0.7 mm/year between 118° and 119.2°W and to 12.5 ± 1.5 mm/year between 119.9° and 120.2°W. Thus, 2.8 ± 0.5 mm/year of relative motion occurs across the Wasatch and related faults in central Utah, 3.7 ± 0.8 mm/year of relative northward motion occurs across the CNSZ, and an additional 6.0 ± 1.6 mm/year is accommodated within the SNTZ. The latter value is within the range of the ~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 ~295° 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 ~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 ±15° 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–bounding 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 ~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-
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 dip-slip faults, and the width of the deformation models are undoubtedly oversimplified. For example, in the CNSZ and SNTZ can be inferred from 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 decreases near the White River, a zone that is consistent with our data. An inferred linear east-to-west trend in the west 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.

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$$F = \rho g h (\sin \gamma - \rho_m \rho_c \sin \beta),$$

where $\rho$ is crustal density, $\rho_m$ is mantle density, $g$ is the gravitational acceleration, and $\gamma$ is the crustal thickness of the low-lying region. $h = 3300 \text{kg m}^{-3}$, $\rho_m = 2750 \text{kg m}^{-3}$, and $\beta = 1$, then $F = 2 \times 10^4 \text{N m}^{-1}$, which is comparable to many plate-driving and resisting forces. This force produces stress anomalies in the elevated region and compressional stress in the adjacent lower lying crust (see D. L. Turcotte, in Mountain Building Processes, K. Hsu, Ed., Academic Press, London, 1982), pp. 141–146). The magnitude of these forces will differ if lateral density contrasts extend into the mantle. For example, the driving force will be smaller than computed above if the mantle lithosphere is colder and thicker beneath the Sierra Nevada and Colorado Plateau than it is beneath the Basin and Range.

9. We assume that principal stress orientations estimated from earthquake fault plane solutions, borehole elongations, and slip vector directions 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.

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14. 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 of 2 mm/year across the Drummond fault. These slip rates are surprisingly high and may be related to a diapiric step fault not modeled. Near 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).

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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 multiband 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 × 10^6 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.

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 border between stars and BDs is estimated to be at about 0.075 solar mass (M⊙) for solar metallicity (2). The deuterium burning limit is at a mass of about 13 M⊙, where M denotes a Jupiter mass (M⊙) (3). We adopt this mass to separate BDs from planets in order to avoid the problems of a definition based on poorly understood formation mechanisms (4). For many years, BDs have eluded firm detection, but since 1995 several objects have been shown to be unambiguously substellar (5, 6). The evidence for BDs is based on observations of lithium (7), luminosity, and surface temperatures (8). However, no direct mass measurement of a brown dwarf has been obtained to date. We present here the first object for which this can be done in the near future.

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 DENIS survey) provided three objects (11) with I-J colors redder than GD 165B, which was the coolest BD candidate known before the discovery of Gl 229B (12). The surface temperatures of Kelu 1 and the DENIS objects are not obviously low enough to establish a substellar status, because young BDs and very low-mass stars can have the same effective temperature. The necessary distinctive substellar signature came from the spectroscopic detection of lithium in the atmospheres of Kelu 1 and DENIS-P J1228.2-1547 (hereafter abbreviated as DENIS 1228-15) (13). On the other hand, in very low-mass stars, the temperature and pressure at the bottom of the convection zone are high enough so that lithium gets rapidly destroyed through proton capture. The combination of high lithium abundance with low surface temperature implies that Kelu 1 and DENIS 1228-15 must have masses lower than 0.065 M⊙ and ages younger than 10^6 years (1 Gy) (13).

We observed DENIS 1228-15 and Kelu 1 with NICMOS camera 1 (NIC1) on the Hubble Space Telescope (HST). The NIC1 data of DENIS 1228-15 were obtained on 2 June 1998 in multiple-accumulate mode with filters F110M, F145M, and F165M (14). This instrumental configuration provides an optimal combination of throughput and spatial resolution. Our observations of Kelu 1 were obtained using the same configuration on 14 August 1998. The NIC1 images of DENIS 1228-15 resolved two components of similar brightness (Fig. 1). To evaluate the parameters of this binary system, we used an iterative approach: We modeled the data assuming two point sources and using both model and observed point spread functions (PSFs). The positions and the brightness ratios of the two point sources were free parameters, and the iterations continued until the residuals were similar to the noise. 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 (15) 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 arc sec/pixel undersamples the PSF (theoretical full width at half maximum of 0.16 arc sec at 1.87 μm). 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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