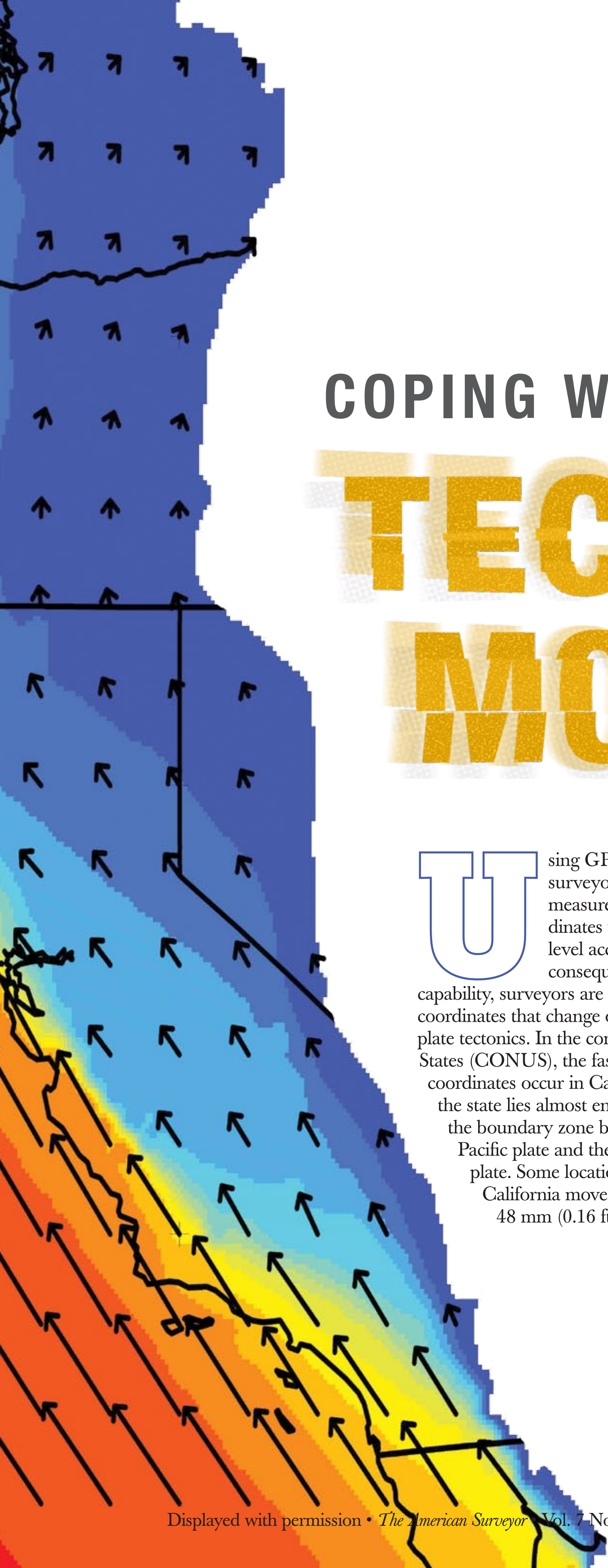


COPING WITH TECTONIC MOTION

Using GPS technology, surveyors can easily measure positional coordinates with centimeter-level accuracy. As a consequence of this capability, surveyors are now exposed to coordinates that change over time due to plate tectonics. In the contiguous United States (CONUS), the fastest changes in coordinates occur in California, because the state lies almost entirely within the boundary zone between the Pacific plate and the North America plate. Some locations in coastal California move approximately 48 mm (0.16 ft) per year relative to the stable interior of CONUS. Measurable tectonic motion also extends well beyond California. As seen in **Figure 1**, parts of Washington, Oregon, and Nevada are also moving in excess of 4 mm (0.013 ft) per year relative to stable CONUS. Such motions demonstrate that Earth's outer shell, called the *crust*, is deformable. It is difficult to imagine rock deforming; however, if we can imagine clamping one end of a kilometer-long rod of solid rock into an unmovable vice, with Superman himself positioned at the opposite end, the Man of Steel would be able to flex the rod by displacing his end several millimeters (or several parts per million) before the rod would break.

>> By Richard Snay and Chris Pearson

The flow of molten rock within Earth's interior and other forces drive the various plates to move in different directions from one another. This motion of the plates across Earth's surface is retarded by friction within the boundary zones between the plates. As a result, the plate boundary zones will gradually deform, and in doing so, elastic restoring forces will accumulate within these zones over time. When these restoring forces overcome the friction, an earthquake occurs with associated slip on a geologic fault, and within a few minutes the area near the earthquake returns somewhat to its original shape.

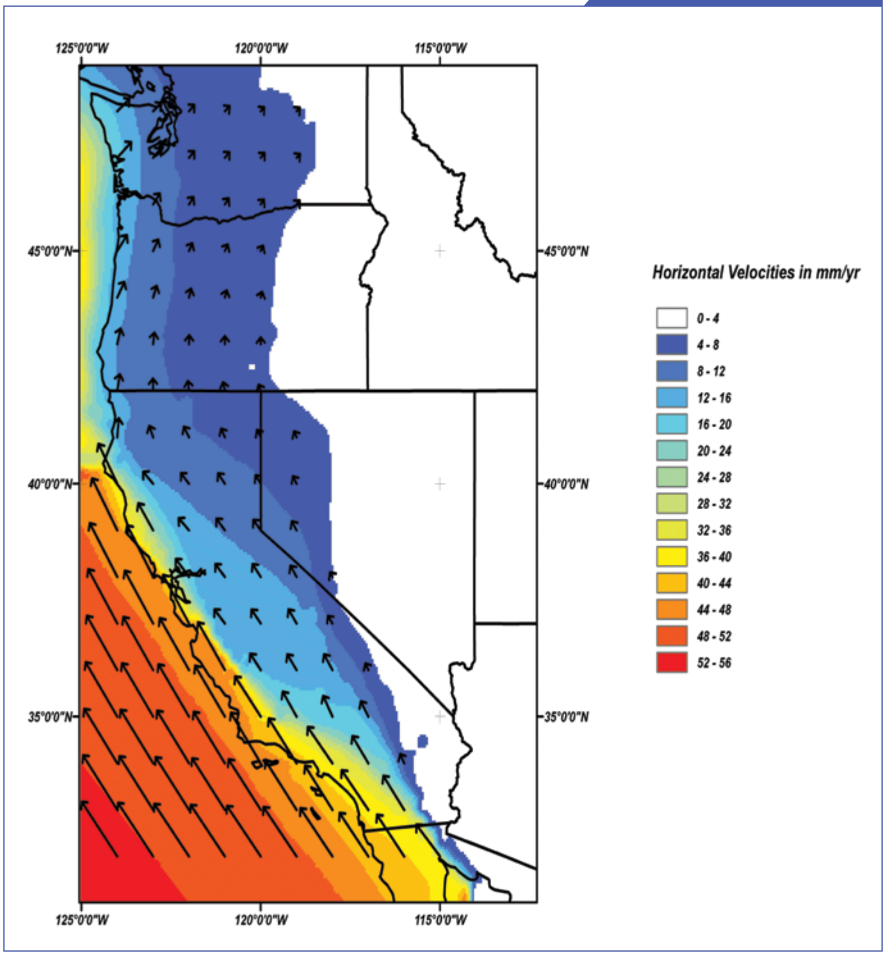
The boundary between two plates is not simply a major geologic fault (like California's San Andreas fault), but rather it includes a zone of deformation that may extend several hundred kilometers in width. Inside this zone, a system of geologic faults is likely to exist where, during past earthquakes, Earth's crust fractured when the elastic restoring forces (due to crustal deformation) exceeded the strength of the local rock.

The Pacific and North America plates are not the only tectonic plates contributing to crustal deformation in western CONUS. Extending from California's Cape Mendocino northward to British Columbia, a collection of three smaller tectonic plates–the Gorda plate, the Juan de Fuca plate, and the Explorer plate–is colliding with the North America plate at a rate of approximately 4 cm (0.13 ft) per year (**Figure 2**). Because each of these three plates is composed of rocks of greater density than the rocks that form the North America plate, these three plates actually *subduct* or are driven beneath the North America plate. The primary interface between the combined three plates and the North America plate intersects Earth's surface several tens of kilometers west of the Washington-Oregon-northern California coastline, and this interface dips downward to the east (**Figure 3**). Similar subduction zones occur off the coast of Chile, the east coast of Japan, and the south coast of the Aleutian Islands. Such subduction zones experience some of the largest earthquakes that have occurred around the globe.

To help surveyors and others cope with tectonic motion, NOAA's National Geodetic Survey (NGS) has developed the *horizontal time-dependent positioning* (HTDP) software. This software incorporates numerical models for plate motion allowing users to apply HTDP to estimate horizontal velocities on Earth's surface anywhere in CONUS, as well as in parts of Alaska.

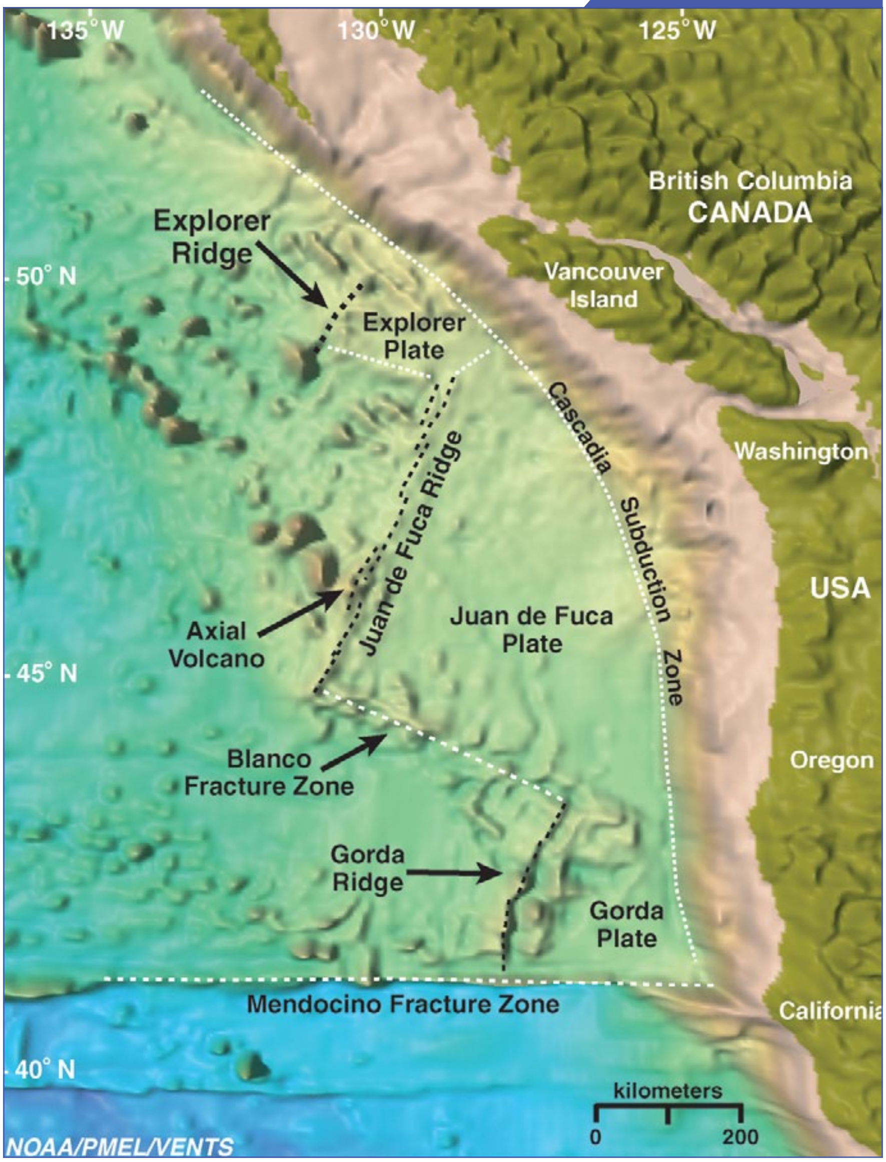
HTDP also incorporates numerical models for most of the recent U.S. earthquakes of magnitude greater than 6.0 on the Richter scale. These models enable HTDP users to estimate the crustal displacements associated with the earthquakes. Taken together, the crustal velocity models and the earthquake models enable HTDP users to update (or backdate) horizontal coordinates measured on one date to corresponding coordinates that would have been measured on another date. These models also enable HTDP users to update (or backdate) the values of certain types of surveying observations–including interstation GPS vectors (also called GPS baselines), distances, angles, and azimuths–from the values measured on one date to those that would have been measured on another date. NGS recently used this capability to update two decades' worth of interstation GPS vectors observed in California, to corresponding values as if these GPS vectors had all been observed on January 1, 2007. The "time-homogenized" GPS observations were then adjusted simultaneously to obtain coordinates for the survey monuments referenced to the realization of the North American Datum of 1983 known as NAD 83 (NSRS2007). The resulting coordinates thus correspond to the locations of the survey monuments on January 1, 2007, denoted as 2007.00 when expressed in decimal years.

FIGURE 1



Horizontal velocities in western CONUS relative to NAD 83 (CORS96) as estimated using HTDP 3.0. Colors indicate velocity magnitudes and arrows indicate velocity directions.

FIGURE 2

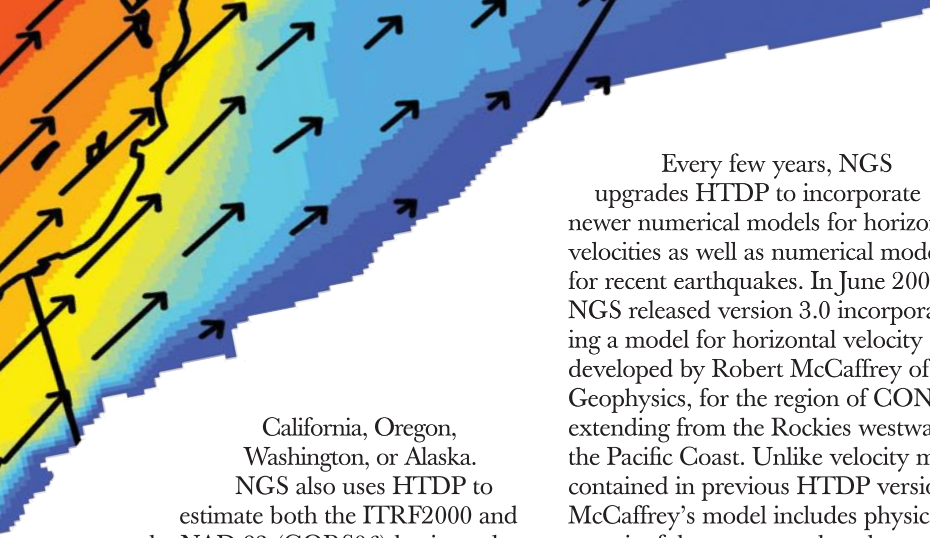


Satellite imagery of the northeast Pacific Ocean. The Explorer, Juan de Fuca, and Gorda Ridges constitute part of the boundary between the Pacific plate and the Juan de Fuca/Explorer/Gorda plates. The Cascadia Subduction Zone is also highlighted, which is the area where the oceanic crust of these three small plates is subducting beneath the North America plate, causing significant crustal deformation in British Columbia, Washington, Oregon, and northern California. *Image courtesy of Submarine Ring of Fire 2002, NOAA's Office of Ocean Exploration and Research (oceanexplorer.noaa.gov/explorations/02fire/background/plan/media/nepac.html).*

HTDP also enables its users to rigorously transform positional coordinates and velocities between the realization of the North American Datum of 1983 known as NAD 83 (CORS96) and other popular terrestrial reference frames, including all realizations of the International Terrestrial Reference System (ITRS) and all realizations of the World Geodetic System of 1984 (WGS84). It should be mentioned that NAD 83 (NSRS2007) is a close approximation to NAD 83 (CORS96). Thus, HTDP treats these two frames as equivalent.

NGS' Online Positioning User Service (OPUS) uses HTDP in two ways. OPUS is a Web-based utility that accepts a user-supplied GPS data set and then computes coordinates for the location where these data were collected. Internal to OPUS, the software currently processes all GPS data so the computed coordinates are referred to the International Terrestrial Reference Frame of 2000 (ITRF2000). Moreover, these computed coordinates are referred to the midpoint of the GPS observing time interval. Firstly, OPUS applies HTDP to convert the ITRF2000 coordinates to corresponding NAD 83 (CORS96) coordinates, both referred to the midpoint of the observing session. Secondly, OPUS applies HTDP to convert the NAD 83 (CORS96) coordinates referred to the midpoint of the observing session, to corresponding NAD 83 (CORS96) coordinates that would have been observed on January 1, 2002 (or 2002.00), except in Alaska (where 2003.00 is used) due to large displacements associated with the November 2002 Denali earthquake (**Figure 4**).

NGS plans to update OPUS in the near future to process all GPS data so that the computed coordinates are referred to the newly derived terrestrial reference frame known as ITRF2008. The updated OPUS utility will then apply HTDP to convert these ITRF2008 coordinates, referred to the midpoint of the GPS observing session, to corresponding NAD 83 coordinates, probably referred to 2010.00 (decision pending). Note that published NAD 83 (NSRS2007) coordinates for passive reference stations (as archived in the NGS Integrated Data Base) are referred to 2007.00. Thus, before comparing these coordinates with coordinates generated by OPUS, surveyors and others should apply HTDP to bring all coordinates to a common date of reference. The use of HTDP to synchronize coordinates is especially recommended for survey work performed in



California, Oregon, Washington, or Alaska. NGS also uses HTDP to estimate both the ITRF2000 and the NAD 83 (CORS96) horizontal velocities for newly established continuously operating reference stations (CORS). HTDP-estimated vertical velocities are zero in value. With these estimated velocities, NGS is able to provide up-to-date coordinates for the CORS, as these coordinates change over time, to support those applications requiring centimeter-level precision. After a CORS has been operational for over three years, NGS supersedes its HTDP-estimated velocity with a velocity computed directly from observations collected at that CORS.

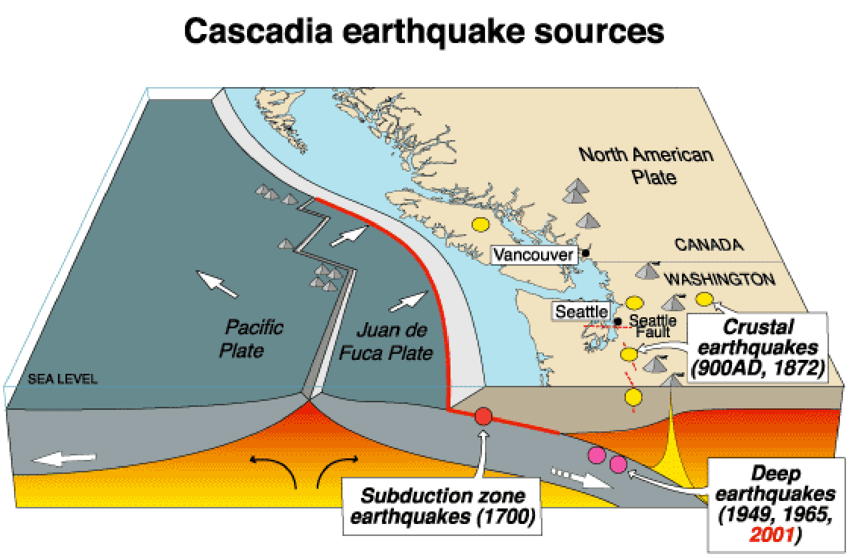
Every few years, NGS upgrades HTDP to incorporate newer numerical models for horizontal velocities as well as numerical models for recent earthquakes. In June 2008, NGS released version 3.0 incorporating a model for horizontal velocity developed by Robert McCaffrey of Troy Geophysics, for the region of CONUS extending from the Rockies westward to the Pacific Coast. Unlike velocity models contained in previous HTDP versions, McCaffrey's model includes physically meaningful parameters that characterize the locations of major geologic faults and the slip occurring on these faults, among other quantities. McCaffrey employed over 4,000 horizontal velocity vectors derived from repeated GPS measurements, in some cases spanning more than a decade. He used these vectors, together with other geophysical data, to rigorously estimate the values of his model's parameters.

NGS collaborated with scientists from the California Spatial Reference Center in determining the standard errors of HTDP-estimated velocities to be less than 2 mm (0.006 ft) per year in each horizontal dimension, north-south and east-west. McCaffrey's models yield more accurate velocities, but some of the model's accuracy was lost when his results were gridded within HTDP to a rectangular array of points spanning western CONUS. HTDP's grid size ranges from 15' by 15' in areas where velocities change slowly with location, to 3.75' by 3.75' in areas where velocities change rapidly with location; such as in California, Oregon, and Washington. HTDP 3.0 also introduced a numerical model for the magnitude 7.9 Denali earthquake that occurred in central Alaska on November 3, 2002. This earthquake model was developed by Julie Elliott and her colleagues at the University of Alaska in Fairbanks.

Particular shortcomings in HTDP 3.0 occur in estimating velocities near the San Andreas fault and also in the vicinities of recent earthquakes and/or volcanic activity. Future HTDP versions will address these shortcomings. A much improved model for estimating velocities in Alaska is also being planned. The current Alaskan velocity model was developed in 2001, and it suffers in accuracy and coverage due to the lack of geophysical data–especially repeated GPS observations–in existence at that time.

To date, HTDP addresses only motion associated with plate tectonics and earthquakes. Significant crustal motion also occurs as a result of volcanic/magmatic activity, glacial isostatic adjustment (also called postglacial rebound), withdrawal of subsurface fluids (water and petroleum), sediment compaction, and various types of crustal loading (tidal, atmospheric, hydrologic). Moreover, these motions occur in all three dimensions. Hence, NGS is planning to create a three-dimensional version of HTDP which may simply be called TDP for time-dependent positioning. The availability of a tool for estimating vertical crustal motion, as well as horizontal crustal motion, is especially important for maintaining accurate

FIGURE 3



Source	Affected area	Max. Size	Recurrence
Subduction Zone	W.WA, OR, CA	M 9	500-600 yr
Deep Juan de Fuca plate	W.WA, OR,	M 7+	30-50 yr
Crustal faults	WA, OR, CA	M 7+	Hundreds of yr?

Various types of earthquakes, some possibly as large as magnitude 9, occur as a result of the Juan de Fuca plate subducting beneath the North America plate. *Image courtesy of Wikipedia (en.wikipedia.org/wiki/Cascadia_subduction_zone).*

FIGURE 4

This segment of Alaska's Richardson Highway experienced an 8.5 foot lateral offset during the M7.9 Denali earthquake of November 3, 2002. This location is near where supports to the Trans Alaska Pipeline sustained damage. *Image courtesy of the U.S. Geological Survey (earthquake.usgs.gov/earthquakes/eqinthenews/2002/uslbbl).*

vertical coordinates on passive reference stations, because observations to measure such coordinates are performed so infrequently. To some unknown degree, the lack of such a tool compromised the accuracy of the NAD 83 (NSRS2007) ellipsoid heights that were calculated in 2007 for ~70,000 passive reference stations distributed across the nation using GPS observations spanning approximately two decades.

At this time, a current NGS project is underway to estimate three-dimensional velocities for all stations in the United States CORS network that have been operational for at least three years. NGS expects the computations of these CORS velocities to be completed by the fall of 2010. NGS will then embark on developing a model to estimate the three-dimensional velocity at any location in CONUS. A TDP release date occurring during the 2011-2012 winter is anticipated.

The current version of HTDP is available for download at *http://www.ngs.noaa.gov/TOOLS/Htdp/Htdp.shtml,* along with instructional information. Users may also operate HTDP interactively at this Web site. Details about the development of HTDP 3.0 may be found in a scientific paper published in the May 2010 issue of the *Journal of Surveying Engineering*.

Richard Snay served as a scientist with the National Geodetic Survey (NGS) until retiring in May 2010. He managed the U.S. CORS program from 1998 to 2007, and he supervised the NGS Spatial Reference System Division from 2003 to 2010.

Chris Pearson has worked as an NGS scientist since 2001. He earned his PhD from the University of Otago in New Zealand. Before joining NGS, he performed research in crustal dynamics at Lamont Doherty Earth Observatory (Columbia University). He currently serves as the NGS geodetic advisor to the State of Illinois.