Appendix : GPS data analysis and data interpretation

GPS data analysis and transient deformation

Velocities of GPS sites throughout Japan are derived from combination of SINEX (Solution INdependent EXchange format) files provided to us by the Geographical Survey Institute (GSI; http://mekira.gsi.go.jp/) from their daily processing of the continuous GPS Earth Observation Network (GEONET) network in Japan (~1200 CGPS sites in total) (Miyazaki et al., 1998; Sagiya et al, 2000). The daily network processing of the GEONET network is conducted by GSI (Sagiya et al., 2000), with Bernese GPS processing software (Rothacher and Mervart, 1996; Beutler et al., 2001) using standard processing methods. The SINEX files we use are from one day every three months for the period 1996-2004. In order to combine the daily SINEX files to estimate velocities for the CGPS sites in Japan relative to a known terrestrial reference frame, we use GLOBK software (e.g., Herring, 2001). To help place the Japanese dataset in a global context, we also use daily solutions from Scripps Institute of Oceanography processing of the global IGS network of GPS sites (http://sopac.ucsd.edu), as well as SINEX files from processing of a subset of ~10 Japanese sites and several global sites that have been submitted by GSI to the Crustal Dynamics Data Information System (CDDIS; http://cddis.gsfc.nasa.gov/). Using GLOBK we estimate a rotation and translation of each dataset into the ITRF2000 reference frame (Altamimi et al., 2002), for each day. To accomplish this, we tightly constrain the coordinates of a subset of the most reliable IGS GPS stations to their known ITRF2000 values. We do this for each set of daily solutions to obtain a time series of site positions in the ITRF2000 reference frame. The ITRF2000 velocities at each GPS station are calculated by a linear fit to the daily ITRF2000 coordinates. The uncertainties in the linear fits are derived using a white-noise model, so the uncertainties are seriously underestimated (e.g., Zhang et al., 1997; Williams et al., 2004). We multiply the formal uncertainties by 5 to give "reasonable" values of about 1 mm/yr uncertainty in horizontal velocities for long-running stations within Japan (T. Nishimura, pers. comm., 2005). Ideally, the GPS velocity errors should be assessed more rigorously. This will require maximum-likelihood analysis of (probably daily, perhaps weekly) time series of GPS positions, to define the appropriate noise model for the data and to calculate a realistic velocity uncertainty (e.g., Williams et al., 2004; Langbein, 2004).

It is very important to avoid the effects on our velocity estimates from earthquakes and slow slip events. The major events influencing the GPS time series in Kyushu from 1996-early 2004 are coseismic and postseismic displacements from two large thrust earthquakes (Ms = 6.7) near Hyuga-nada in 1996 (Yagi et al., 2001), the 1996-1997 Bungo Channel slow slip event (Hirose et al., 1999), and the 1997 Kagoshima-ken-hokuseibu earthquake (Fujiwara et al., 1998). To remove the influence of these transient displacements from the time series, we removed the time series data prior to 1998 in the regions affected by these events. Moreover, to avoid influence from the 2003 Bungo Channel slow slip event (Hirose and Obara, 2005), we did not include data from that region later than early 2003. GPS sites in the Kagoshima region were affected by an inflation event at Aira caldera throughout the GPS measurement period (Kriswati and Iguchi, 2003); we used Mogi source parameters for the inflation event estimated by Nishimura et al. (2004) to remove this effect from the dataset. We also conducted a visual inspection of the daily GPS position time series for all the sites in Kyushu and the southwest Honshu region to ensure that our velocity estimates do not include non-linear behavior that does not represent steady movement during the interseismic period.

We also used in our inversion other published GPS velocity fields from Heki et al. (1999), Calais et al., (2003), Sella et al. (2002), Beavan et al. (2002), and Prawirodirdjo and Bock (2004) to help place the Kyushu velocities into a regional kinematic context.

Interpretation of GPS velocities using the elastic block approach

To interpret the GPS velocities, we use an approach developed by McCaffrey (2002) which performs a non-linear inversion to simultaneously estimate the angular velocities of elastic blocks and coupling coefficients on block-bounding faults, to give the best fit to the GPS velocities, and optionally, earthquake slip vectors, and geological fault slip rates and azimuths. The data misfit, defined by the reduced chi-squared statistic (χ_n^2), is minimized. The method also allows us to optimally rotate multiple GPS velocity solutions into a common reference frame.

In the block models presented here, we define a Eurasian Plate, Amurian Plate, Philippine Sea Plate, and Southwest Japan Block (Fig. 3). We define most of the boundaries of the large plates (Amurian, Philippine Sea and Eurasian Plates) based on a digital compilation of tectonic plate boundaries by Bird (2003). The inclusion of these larger plates also helps us in establishing the overall plate motion budget that must occur across the plate boundary zone in southwest Japan. The Southwest Japan/Amurian Block boundary is defined by a zone of distributed faulting and historical strike-slip earthquakes near the west coast of Japan (Gutscher and Lallemand, 1999).

We have tested a variety of scenarios for dividing the forearc in southwest Japan into blocks. The three models we present here, are (1) where the forearc region (e.g., Satsuma, Ohsumi and eastern Kyushu blocks) constitutes a single block, (2) where the forearc is divided into two blocks (an eastern Kyushu block, and a combined Satsuma and Ohsumi block), and (3) where the Satsuma, Ohsumi and eastern Kyushu blocks are three separate forearc blocks (Fig. 3). These three models allow us to test whether or not the proposed left-lateral shear zone is required by the GPS data, and also to test for possible crustal deformation in the Kagoshima Graben region. For details of model results see discussion in main manuscript. In all models presented here, we also include a separate Shikoku block, bounded to the northwest by the Median Tectonic Line and bounded to the southeast by the Nankai Trough. The Ohsumi block is bounded to the west by the Kagoshima graben, and to the north by the left-lateral shear zone that we identify from GPS site velocities and seismicity (e.g., Kodama et al., 1995; Nishimura and Hashimoto, 2006). We use the Kagoshima graben as a boundary in some of our models based on evidence from GPS (Fig. 3) and geology (Aramaki, 1984) for active extension in the Kagoshima Graben, and paleomagnetic evidence that southeast Kyushu (east of the Kagoshima graben) has rotated independently of the rest of Kyushu for the last 2-6 Myr (Kodama et al., 1995). The Satsuma block is bounded on the east by the Kagoshima graben and on the north by the hypothesized active left-lateral shear zone. The eastern Kyushu block encompasses more than half of the Kyushu forearc, whose western boundary is the Beppu-Shimabara graben.

To define the subduction interface fault (Nankai Trough and Ryukyu Trench), we use the configuration for the Nankai subduction interface from Shiomi et al. (2004) (Fig. 3). Individual nodes on the subduction interface are defined at an average spacing of ~50 km apart along strike, and at 10 km depth intervals between 0 and 50 km depth (Fig. 3). We define the Median Tectonic Line as a northward dipping fault, based on geophysical evidence (Ito et al., 1996). We approximate the Beppu-Shimabara Graben (BSG) boundary as a single fault in the model, although more complex deformation on several faults across a zone is likely to be a more realistic scenario there (Kamata and Kodama, 1994). We set the BSG fault to dip northwest, in part, to deal with possible distributed deformation due to faulting northwest of our prescribed boundary. McCaffrey's (2002) method is used to solve for coupling coefficients at nodes on the Nankai Trough and Ryukyu Trench, the fault representing the BSG, the Median Tectonic Line, and, in some cases, the faults representing the extensional zone in the Kagoshima Graben and a possible zone of left-lateral strike-slip cross-cutting southeast Kyushu (Fig. 3). To represent the change in coupling coefficient (ϕ) values between adjacent nodes, ϕ values on 5 km x 5 km rectangular fault patches between the nodes are estimated by bilinear interpolation. Additional free parameters in the inversion are the rotation parameters (three for each block) for the tectonic blocks relative to a fixed Eurasian-plate, and rotation parameters that rotate each GPS velocity dataset into a Eurasia-fixed reference frame. Inversion results for the three models are discussed in more detail in the main manuscript.

References cited in Appendix:

Altamimi, Z., P. Sillard, and C. Boucher, 2002, ITRF2000: A new release of the International Terrestrial Reference Frame for earth science applications, J. Geophys. Res., 107(B10), 2214, doi:10.1029/2001JB000561.

Aramaki, S., 1984, Formation of the Aira Caldera, southern Kyushu, 22,000 years ago, J. Geophys. Res., 89(B10), 8485-8501.

Beutler, G., H. Bock, E. Brockmann, R. Dach, P. Fridez, W. Gurtner, U. Hugentobler, D. Ineichen, J. Johnson, M. Meindl, L. Mervart, M. Rothacher, S. Schaer, T. Springer, R. Weber (2001), Bernese GPS Software Version 4.2, Ed. by U. Hugentobler, S. Schaer, P. Fridez, *Astronomical Institute, University of Berne.*

Beavan, J. Tregoning, P., Bevis, M., Kato, T., and Meertens, C., 2002, Motion and rigidity of the Pacific plate and implications for plate boundary deformation: Journal of Geophysical Research, v. 107, p. 2261-2276.

Bird, P., 2003, An updated digital model of plate boundaries, Geochem. Geophys. Geosyst., 4(3), 1027, doi:10.1029/2001GC000252.

Calais E., Vergnolle, M., San'kov, V., Lukhnev, A., Miroshnitchenko, A., Amarjargal, S., Déverchère, J., 2003, GPS measurements of crustal deformation in the Baikal-Mongolia area (1994–2002): Implications for current kinematics of Asia, Journal of Geophysical Research, v. 108, B102501.

Fujiwara, S., H. Yarai, S. Ozawa, M. Tobita, M. Murakami, H. Nakagawa, and K. Nitta, 1998, Surface displacement of the March 26, 1997, Kagoshima-ken-hokuseibu earthquake in Japan from synthetic aperture radar interferometry, Geophys. Res. Lett., 25(24), 4541-4544.

Gutscher, M.-A., and S. Lallemand, 1999, Birth of a major strike-slip fault in SW Japan, Terra Nova, 11(5), 203-209.

Heki, K., S. Miyazaki, H. Takahashi, M. Kasahara, F. Kimata, S. Miura, N. Vasilenko, A. Ivashehenko, and K.-D. An, 1999, The Amurian plate motion and current plate kinematics in Eastern Asia, Journal of Geophysical Research, v. 104, p. 29147-29155.

Herring, T. A., 2001, GLOBK global Kalman filter VLBI and GPSanalysis program, version 5.03, Massachusetts Institute of Technology, Cambridge.

Hirose, H., K. Hirahara, F. Kimata, N. Fujii, and S. Miyazaki, 1999, A slow thrust slip event following the two 1996 Hyuganada earthquakes beneath the Bungo Channel, southwest Japan, Geophys. Res. Lett., 26(21), 3237-3240.

Hirose, H., and K. Obara, 2005, Repeating short- and long-term slow slip events with deep tremor activity around the Bungo Channel region, southwest Japan, Earth, Planets and Space, v. 57, p. 961-972.

Ito, T., T. Ikawa, S. Yamakita, and T. Maeda, Gently north-dipping Median Tectonic Line (MTL) revealed by recent seismic reflection studies, southwest Japan, *Tectonophys.*, 264, 51–63, 1996.

Kamata, H., and Kodama, K., 1994, Tectonics of an arc-arc junction: an example from Kyushu Island at the junction of the Southwest Japan Arc and the Ryukyu Arc: Tectonophysics, v. 233, p. 69–81, doi: 10.1016/0040-1951(94)90220-8.

Kodama, K., Tashiro, H., and Takeuchi, T., 1995, Quaternary counterclockwise rotation of south Kyushu, southwest Japan: Geology, v. 23, p. 823–826, doi: 10.1130/0091-7613(1995)023<0823:QCROSK>2.3.CO;2.

Kriswati, E. and Iguchi, M., 2003, Inflation of the Aira Caldera prior to the 1999 eruptive activity at Sakurajima Volcano detected by GPS network in south Kyushu, Disaster Prevention Research Institute Report, 46, 817-825.

Langbein J., 2004, Noise in two-color electronic distance meter measurements revisited, *J. Geophys. Res., 109*, B04406, doi:10.1029/2003JB002819.

McCaffrey, R., 2002, Crustal block rotations and plate coupling, in Stein, S., and Freymueller, J., eds., Plate boundary zones: American Geophysical Union Geodynamics Series 30, p. 100–122.

Miyazaki, S., Y. Hatanaka, T. Sagiya, and T. Tada, 1998, The nationwide GPS array as an Earth Observation System, Bulletin of the Geographical Survey Institute, v. 44, p. 11-22.

Nishimura, S., Hashimoto, M., and Ando, M., 2004, A rigid block rotation model for the GPS derived velocity field along the Ryukyu arc, Physics of the Earth and Planetary Interiors, v. 142, p. 185-203.

Nishimura, S. and M. Hashimoto, 2006, A model with rigid rotations and slip deficits for the GPS-derived velocity field in Southwest Japan, *Tectonophysics, 421*, 187-207.

Prawirodirdjo, L. and Y. Bock (2004): Instantaneous global plate motion model from 12 years of continuous GPS observations, Journal of Geophysical Research., v. 109, B08405.

Rothacher, M., and L. Mervart (eds.), Documentation of the Bernese GPS Software Version 4.0, 418 pp, Astron. Inst., Univ. of Bern, Bern, Switzerland, 1996.

Sagiya, T., S. Miyazaki, and T. Tada (2000), Continuous GPS array and present-day crustal deformation of Japan, *Pure and Applied Geophysics,* 2303-2322.

Sella, G.F., Dixon, T.H., and Mao, A.L., 2002, REVEL: A model for recent plate velocities from space geodesy, Journal of Geophysical Research, v. 107, 2081-2112.

Shiomi, K., Sato, H., Obara, K., and Ohtake, M., 2004, Configuration of the subducting Philippine Sea plate beneath southwest Japan revealed from receiver function analysis based on multivariate autoregressive model: Journal of Geophysical Research, v. 109, p. B04308, doi: 10.1029/2003JB002774.

Williams S. D. P., Y. Bock, P. Fang, P. Jamason, R. M. Nikolaidis, L. Prawirodirdjo, M. Miller, D. J. Johnson (2004), Error analysis of continuous GPS position time series, *J. Geophys. Res., 109,* B03412, doi:10.1029/2003JB002741.

Yagi, Y., M. Kikuchi, and T. Sagiya, 2001, co-seismic slip, post-seismic slip, and aftershocks associated with two large earthquakes in 1996 in Hyuga-nada, Japan, *Earth Planets Space, 53,* 793-803.

Zhang, J., Y. Bock, H. Johnson, P. Fang, S. Williams, J. Genrich, S. Wdowinski, and J. Behr (1997), Southern California Permanent GPS Geodetic Array: Error analysis of daily position estimates and site velocities, *J. Geophys. Res.*, *102*(B8), 18,035–18,056.