A GLOBAL POSITIONING SYSTEM EXPERIMENT IN THE ANDES

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Abstract:

A geodetic experiment is being planned to measure the convergence between the Nazca and the South American plates and its relationship to shortening and uplift within the Andes. The experiment will employ Global Positioning System (GPS) receivers operated simultaneously at Juan Fernandez and San Felix Islands, the Andean mainland, and 10 or more globally distributed tracking sites. The Andean portion of the experiment will consist of networks bounding the major subdivisions of the Andes in both a north-south and east-west sense. This coverage should allow increased understanding of the interaction between the four major segments of the subducting oceanic slab with tectonic elements of the overlying continental plate.

Introduction:

NASA's Jet Propulsion Laboratory in conjunction with Northwestern University and the Carnegie Institution is currently in the early stages of planning for a space-based geodetic experiment in the southeast Pacific and Andes beginning in 1991, using the Global Positioning System (GPS). This experiment, known as SNAPP (South America-Nazca Plate Project) is designed to monitor subduction and key aspects of Andean tectonics. GPS is a highly accurate space-based geodetic technique that, for the first time, offers the flexibility and portability for economically measuring a relatively dense geodetic network extending several thousand kilometers at centimeter accuracy. The experiment being planned involves multiple measurements of baselines between south Pacific islands and the mainland of western South America, a dense network across the Andes, and a globally distributed tracking network. Multiple GPS campaigns made a few years apart will allow direct measurement of the rate of subduction across the trench as well as the rate of horizontal shortening and vertical uplift across individual tectonic provinces of the Andes and relationships to differences in the subduction of the Nazca oceanic plate. In this abstract, we briefly describe the scientific rationale for the Andean part of this experiment and some aspects of the GPS geodetic technique.

Nazca Plate Subduction and Segmentation:

Subduction of the Nazca plate beneath South America occurs along four major segments defined by the seismicity of the Benioff zone (e.g., 1-5). Two segments, one beneath Peru (2°S to 15°S) and the other beneath middle Chile and Argentina from 27°S to 33°S, have very shallow dips of 5°-10° to the east. The other two segments, one between the flat-plate segments described above and the other south of 33°S, dip at about 30° to the east. The rate of convergence between the Nazca and South American plates has been estimated at 8.3 cm/yr from global plate motion models, 18.7-12.8 cm/yr from seismic slip, and 6.5 cm/yr from space geodetic measurements (6). Understanding the discrepancies between the different rate estimates and how convergence is apportioned between subduction and deformation in the overlying South American plate is a major goal of SNAPP.

Andean Tectonics:

A direct relationship exists between the segmentation of the subducted Nazca plate and characteristics of the overlying segments of the Andes (7). The region above the 30°-dipping slab in southern Peru, northern Chile and Bolivia (18°S to 27°S) contains a longitudinal valley along the coast that is locally under extension (8). A well developed volcanic arc is composed of Quaternary andesitic stratovolcanoes that make up the crest and the western edge of the high plateaus. The Altiplano-Puna plateaus are internally draining basins that experienced significant uplift at the end of the Neogene. The cause of the plateaus is not known, however Isacks (9) has recently suggested thickening of a lower crustal weak zone since the middle Miocene. To the east of the plateaus lies the hinterland and foreland, which are made up of the Eastern Cordillera and the Subandean belt. The Subandean belt is a thin-skinned fold and thrust belt, that is analogous to the thin-skinned fold and thrust belt of the Canadian Rocky Mountains, and has been active from the Miocene to the present. Earthquake focal mechanisms show this region is still under compression as do Quaternary reverse faults in the Subandean to the north (8). Reverse faults bounding the Subandean belt root beneath the Eastern Cordillera, which is composed of Paleozoic and older strata deformed by thrust faults and high angle reverse faults that were mostly active during the Miocene.

Along the Chile-Argentina flat plate segment (27°S to 33°S) the forearc rises steadily from the arc without a forearc basin or evidence for extensional deformation. Quaternary volcanism is absent and there are only minor older volcanics of Miocene age (10). To the east of the forearc and the crest of the Andes lie the Frontal Cordillera and Precordillera, which are thin-skinned fold and thrust belts. Evidence suggests the Frontal Cordillera was active in the Miocene, whereas the Precordillera has been active in Plio-Pleistocene time, suggestive of an eastward migrating thrust belt. To the east of this thrust belt are the Pampeanas Ranges, a major system of foreland crystalline basement uplifts, 2-4 km to locally 6 km high, 25-75 km wide. These basement uplifts are separated by broad intervening basins (typically wider than the uplifts) at about 1 km elevation. The ranges have been uplifted along north- to northwest-striking reverse faults that dip 30°-60°, based on field observations at the surface and subsurface focal mechanism solutions. The faults commonly have about 6 km of throw and uplift Precambrian and Paleozoic crystalline basement over upper Cenozoic strata. Geologic relations indicate Pliocene-Pleistocene deformation; compressional earthquakes indicates that the deformation is continuing today. A case has been made for the Pampeanas Ranges being analogous to the Laramide foreland basement uplifts of the Rocky Mountains in western North America.

The segment of the Andes above the flat subducting slab in Peru and southern Ecuador (2°S to 18°S) is generally similar to the Chile-Argentina flat plate segment. No forearc basin is reported. The volcanic arc was last active in the middle Miocene, with little or no volcanism since about 5 Ma when flat plate subduction began. Hinterland and foreland folding is reported during the Neogene and into the Quaternary. Foreland basement uplifts are found to the east of the fold belt. These uplifts have many of the same characteristics as the Pampeanas Range, but are less well developed, perhaps due to the younger age of the flat slab in Peru and the implied smaller shortening.

The southern 30°-dipping segment extends south of 33°S to at least 38°S. This segment has an extensional forearc basin, the Central Valley. The Principal Cordillera is a folded and faulted belt deformed from the middle Tertiary to the Miocene. The volcanic arc is well defined by Quaternary basaltic andesite stratovolcanoes. Unlike the 30°-dipping segment to the north the deformation in this segment of the Andes is confined to a narrow zone. To the east of this area exists an enormous field of Miocene to present basalts.

A few other relationships deserve mention. Earthquakes within the upper plate are most frequent and largest in magnitude above the flat plate subduction zones. The forearc and plateaus are for the most part quiet seismically (7). The forearc is locally under extension above the 30°-dipping segments (8) and under compression above the flat plate segments. The hinterland and foreland are consistently under compression along the entire length of the Andes (8, 11). The eastern extent of the deformation in the foreland corresponds to the eastern extent of the Benioff zone in all the segments discussed above. Jordan et al. (1983) suggest that the preexisting structure and geometry of the upper plate may have had an influence on the location and geometry of segments in the subducting plate.

Estimates of the total shortening across the Andes are limited and rates of deformation are uncertain. Geologic reconstructions suggest roughly 20-30% of shortening (60-200 km) across the Subandean fold and thrust belt, depending on latitude (12, 13). Shortening across the Pampeanas is estimated at 10-20 km (14) and about 50 km across the Precordillera at that latitude for a total of about 70 km across this segment. Megard (15) has estimated a little over a hundred kilometers of shortening over part of the Andes in Peru. If this deformation has been occurring over about the past 10 Ma (7), then total rates of shortening across the Andes are of order 1 cm/yr. Isacks (9) has constructed a model for the deformation and uplift of the central Andes that links the horizontal shortening in the foreland thrust belts with the thickening and vertical uplift of the high plateaus. This model predicts from one to a few hundred kilometers of shortening over about 15 Ma, which also suggests a rate of shortening across the Andes of order 1 cm/yr. Isacks' model also predicts decreased shortening away from the Bolivia orocline (the bend in the Andes at about 20°S) and concomitant clockwise rotation of the arc south of the bend and counterclockwise rotation of the arc north of the bend, both of which appear supported by paleomagnetic data (16-18). Uplift of the Andes over the past 10 Ma has been rapid, approaching 1 cm/yr (19, 20).

GPS Geodesy:

The precision and accuracy of GPS geodetic measurements for regional tectonics applications depends on the location of the experiment, baseline length (receiver spacing), experiment design and analytical technique. Numerous GPS experiments have been conducted in southern California, where very long baseline interferometry (VLBI) measurements are available for comparison. These data, as well as GPS data from various other experiments allow us to predict the likely performance of GPS in the Andes.

The repeatability of a GPS measurement is one measure of precision, and for southern California measurements, has proven to be about 5-10 mm plus 1-2 parts in 10^8 of baseline length for the horizontal components (21-23). The accuracy of these measurements is roughly comparable to their repeatability based on comparisons to VLBI data. The precision and accuracy of the vertical component is somewhat worse than the horizontal components, in the range 3-6 cm, and is not correlated with baseline length.

In other regions, the precision and accuracy of GPS may degrade, depending on the level of and analytical treatment for two major GPS errors sources, uncertainties in the positions of the GPS satellites, and signal propagation effects due to the troposphere. Preliminary results from GPS experiments in the Gulf of California (23-25), the northern Caribbean (26) and the northern Andes and Central America (27-29) suggest that these errors can be minimized such that the total uncertainty in the horizontal components of GPS measurements in these regions is no worse than 10 mm plus 2-3 parts in 10^8 of baseline length.

The only impediment to achieving similar results in the central and southern Andes would be increased levels of error associated with satellite orbit uncertainties, caused by greater distance from GPS tracking (fiducial) sites. Typically, GPS data is acquired at these fiducial sites simultaneously with the experiment in the region of interest. The positions of the fiducial sites are known *a priori* from independent measurement, for example by VLBI, thus data from these sites provide independent information on satellite trajectories. We have performed a covariance analysis using synthetic GPS data and proposed site locations, as well as realistic satellite geometries for the early 1990's, to determine quantitatively the level of orbit-related errors for the SNAPP experiment. These studies suggest that accuracy equivalent to that achieved in experiments in the Caribbean and northern South America can be achieved throughout the Andes, providing several tracking sites in the southern hemisphere (e.g., Australia and New Zealand) are employed.

GPS receivers will be placed in three latitudinal bands across provinces within the three segments defined south of 18°S (Fig. 1). In the region above the 30°-dipping slab in southern Peru, Chile and Bolivia receivers will be placed at the east and west ends of the forearc, on either side of the Altiplano, to the east of the Subandean belt, and perhaps between the Subandean and Eastern Cordillera. In the region above the flat slab segment in Chile and Argentina receivers will be placed: on the coast, on the crest of the mountains, between the Precordillera and

Pampeanas and east of the Pampeanas. In the region above the southern 30°-dipping slab receivers will be placed: on the coast, near the arc, and east of the Principal Cordillera. Our first experiment is tentatively planned for 1991, with reoccupations in 1993 and 1995.

References: **1** Stauder, W., 1973, J. Geophys. Res. 78, 5033-5061. **2** Stauder, W., 1975, J. Geophys. Res., 80, 1053-1064; **3** Barazangi, M. & B. Isacks, 1979, Geophys. J. Royal Ast. Soc. 57, 537-555; **4** Isacks, B. & M. Barazangi, 1977, *in* Island arcs, deep sea trenches and back arc basins. Amer. Geophys.Un., 99-114; **5** Hasegawa, A. & I. Sacks, 1981, J. Geophys. Res. 86, 4971-4980; **6** Stein et al., 1986, Geophys. Res. Lett. 13,713-716; **7** Jordan et al., 1983, Geol. Soc. Amer. Bull. 94, 341-361; **8** Sebrier, M.et al., 1985, Tectonics 4, 739-780; **9** Isacks, B., 1988, J. Geophys. Res. 93, 3211-3231; **10** Kay, S., et al., 1988, J. South Amer. Earth Sci. 1, 21-38; **11** Suarez, G. P. Molnar & B. Burchfiel, 1983, J. Geophys. Res., 88, 10,403-10,429; **12** Allmendinger, R.et al., 1983, Tectonics 2, 1-6; **13** Sheffels, B., B. Burchfiel & P. Molnar, 1986, EOS Trans. Amer. Geophys. Un. 44, 1241; **14** Jordan, T. & R. Allmendinger, 1986, Amer. J. Sci. 286, 737-764; **15** Megard, F.,1984, J. Geol. Soc. London 141, 893-900; **16** Beck, M., R. Drake & R. Butler, 1986, Geology 4, 132-126; **17** Beck, M., 1988, J. South Amer. Earth Sci. 1, 39-52; **18** Kono, M., K. Heki & Y. Hamano, 1985, J. Geodyn., 2, 193-209; **19** Crough, T., 1983, Earth Planet. Sci. Lett. 64, 396-397; **20** Benjamin et al., 1987, Geology 15, 680-683; **21** Blewitt, G., 1989, J. Geophys. Res., 94, 10187-10203; **22** Davis, J., W. Prescott, J. Svarc, K. Wendt, 1989, J. Geophys. Res., 94, 13635-13650, 1989; **23** Tralli, D. & T. Dixon, 1988, Geophys. Res. Lett. 15, 353-356; **24** Tralli, D., T. Dixon, & S. Stephens, 1988, J. Geophys. Res. 93, 6545-6557 **25** Dixon. T., et al., 1990, AAPG Mem 47, In Press; **26** Dixon et al., 1990, J. Geophs. Res., in press; **27** Kellogg. J. T. Dixon & R Neilan, 1989, EOS:Trans. Am. Geophys. U. 70, 649-656; **28** Dixon. T. & S. Kornreich Wolf, 1990, Geophys. Res. Lett., In Press; **29** Kornreich Wolf, S., T. Dixon & J. Freymueller, 1990, Geophys. Res. Lett., In Press;

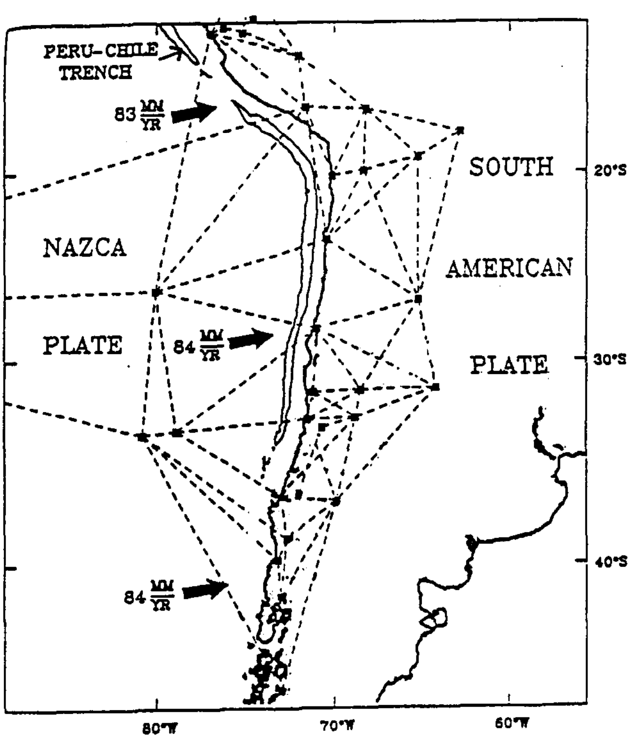

Figure 1. Map of geodetic network planned for the SNAPP experiment. Dashed lines are the baselines to be measured. Plate velocity is shown for reference.