VLBI Detection of Crustal Plate Motion Using DSN Antennas as Base Stations

D.D. Morabito, E. S. Claflin, and C. J. Steinberg
Tracking Systems and Applications Section

Estimated crustal plate motion is presented with respect to each of the three Deep Space Network (DSN) sites, Goldstone, Madrid and Canberra, based on a plate motion model by Minster et al. The technique of Very Long Baseline Interferometry (VLBI) is capable of measuring crustal movements of a few centimeters per year. The estimated crustal movement predicted by the model is compared with apparent movement measured by the ARIES VLBI group at JPL across a plate boundary in Southern California.

I. Introduction

The Earth's crust consists of six or seven major plates and several minor plates. Indirect evidence of various types indicates that these plates are moving with respect to each other with speeds (based on long term data averages) on the order of several centimeters per year. It was only in the last few decades that geologists realized that the Earth's crust is not rigid (Ref. 1), and that the surface features of the Earth are mostly due to the interactions of these plates.

The relative movement between 11 of these plates has been numerically modeled by Minster et al. (Refs. 2 and 3). Minster assumed the plates to be internally rigid, and used existing indirect geological data types consisting of ocean ridge spreading rates, fracture zone trends and earthquake slip vectors to obtain a self-consistent model of instantaneous relative motions. The plate motion model developed yields a parameter known as the rotation rate vector, which describes the rotation of each plate with respect to another reference plate. Using a DSN station as one component of a VLBI (Very Long Baseline Interferometry) interferometer on a reference plate, Minster's model can be applied to predict how much relative movement with respect to the DSN station will be detected using a second station at any point on any other plate. The model predictions are valuable for choosing potential new antenna sites where significant continental drift may be detected and measured.

The VLBI measurement technique has been developed in recent years with applications to geodesy, astronomy, and spacecraft navigation. As a geodetic tool, VLBI has the potential to measure crustal movement with high accuracies, yielding errors as low as a few centimeters on baselines measuring up to several hundred kilometers, and possibly up to intercontinental distances.

Thus, VLBI possesses the potential to make direct measurements of relative crustal plate motion which may be compared with the motions inferred from indirect geological data. Such measurements would allow important geophysical questions to be studied and perhaps answered. One such question asks whether the motion between plates is episodic or relatively continuous. Another important question of concern addresses the relationship between the observed motion and earthquakes. Finally, how do such phenomena as warping and cracking along plate boundaries modify the large scale picture of rigid plate motion? VLBI would be a useful tool in helping to resolve such questions.

Project ARIES (Astronomical Radio Interferometric Earth Surveying) is currently performing geodetic measurements in California (Refs. 4-6). The base stations include the DSN antennas at Goldstone and the Caltech Owens Valley Radio Observatory, both of which reside on the North American plate. The San Andreas fault separates the North American plate from its western neighbor the Pacific plate, which includes much of coastal Southern California. The ARIES 9-meter portable dish antenna has occupied several sites in this coastal region, and hence may be able to directly measure the relative motion of these two plates.

This article discusses the prospects of the VLBI technique for detection and measurement of crustal drift using DSN stations. Potential sites for other, fixed or portable stations are suggested by applying the model developed by Minster. Current measurements from Project ARIES are compared with the crustal model predictions.

II. The Rigid Plate Model

The description of the displacement of a rigid plate on the surface of a sphere may be understood in terms of rigid body motion. The correspondence becomes clear if one imagines that the moving plate contains an embedded set of body axes and the Earth (or another plate) contains the reference axes. The two coordinate systems have common origins at the center of the sphere (Earth). A basic theorem of rigid body motion then assures us that any translation and/or rotation of the plate is describable as purely a rotation about some axis fixed in the reference system and passing through the Earth's center. Simplicity ends here, however, because the sum of two rotation vectors does not, in general, give a displacement equal to the successive application of the individual rotations. However, by writing the coordinate transformation equations in linear approximation, it can be shown that the rotation vectors for small displacements are additive.

The important implications of these results for plate motion are that instantaneous relative motion of two plates can be described completely by a single rotation rate vector and that the relative rotation rates of plates are additive. Thus the Minster et al. data was easily applied to predict plate motion with respect to the DSN antennas for six major plates.

The magnetic anomalies used by Minster to compute spreading rates are as old as several million years. Changes in the instantaneous rotation rate vectors become significant after approximately 10 million years. We will assume that this model is valid for current geological time.

III. Crustal Drift Rates With Respect to DSN Stations

Plate motion has been determined using the rotation rate vectors given by Minster et al. (Ref. 2), using the DSN sites as base stations. Figures 1-3, 4-6, and 7-9 display the plate motions to be expected for reference stations at Goldstone (North American plate), Australia (Indian plate), and Madrid (Eurasian plate), respectively. Displayed for each DSN station is a contour map of constant total velocity magnitude, constant baseline extension rate (movement along the baseline), and constant transverse velocity magnitude (movement perpendicular to the baseline). Each map displays motion with respect to five other plates. The six major plates included on the maps are the North American, Pacific, Indian, Eurasian, African and South American plates. The DSN site is marked on each map with a plus sign. Plate boundaries displayed are not necessarily definitive, but are believed to be accurate enough for the purposes of these maps.

IV. VLBI as a Geodetic Tool

The technique of VLBI may be applied to detect and measure crustal plate drift. The VLBI system consists of two or more radio telescopes widely separated, each residing on different tectonic plates. A VLBI experiment consists of having both antennas of a particular baseline simultaneously observe a sequence of extragalactic radio sources well distributed across the sky. Each experiment usually lasts several hours and each observation of a radio source lasts several minutes. The measured baseline is obtained from a fit using the measurements of the differential time of arrival of the wavefronts from each radio source at the two antennas. The overall theoretical development and data reduction technique is quite involved and will not be discussed here. The reader is referred to the papers by Thomas (Refs. 7 and 8) for more detailed discussions.

By performing VLBI experiments over a period of many years, we have the capability of measuring variations of the baseline vector and hopefully refining current plate motion models significantly. In particular, small scale deformations (deviations from rigid plate theory) may be determined using this technique. Deviations from the rigid plate theory are certain to exist. Plate boundaries are diffuse, small plates do exist, and motion along plate boundaries is not continuous, as exhibited by the existence of earthquakes. Movement along plate boundaries involves slippage to relieve stress. Accumulation of stress can cause a wide zone of deformation across plate boundaries which can go deep within a plate. Also, the motion computed from the rigid plate model is averaged from data which spans millions of years and may vary over shorter time scales.

The two principal components measured by VLBI are the baseline extension component and the transverse velocity component. The baseline extension rate is easily computed by fitting a slope through the solved-for baseline lengths from several VLBI experiments on the same baseline. The baseline length has a very low error since it is a direct consequence of measured delay and does not depend on coordinate orientations. The baseline transverse component may have a higher error since it is dependent on baseline orientations. Therefore, VLBI may measure baseline extension rates more accurately, and this should be taken into consideration when examining these maps for detection opportunities.

The maps indicate some excellent short baseline opportunities in Australia. Short baseline measurements have the advantage over long baseline (intercontinental) measurements of having lower errors and decreased cross-coupling between estimates of baseline components. Using the DSN sites in Canberra, Australia as a base station, some nearby sites where significant baseline extension may be detected and measured are New Zealand, Southeast Asia, and some nearby islands on the Pacific Plate. Movement here is on the 5 cm/year level. Measurements of total velocities will yield larger numbers (~10 cm/year); thus detection is perhaps possible after only a couple of years of observing.

The maps also indicate many long baseline opportunities for detecting crustal movement using Canberra as a base station. In every other crustal plate displayed, total velocities run about 5 cm/year or greater. The Hawaiian islands as a portable site have total velocities with respect to Canberra running about 8 cm/year, with the corresponding extension rate being about −5.5 cm/year. The Goldstone/Canberra baseline has a predicted −3.5 cm/year baseline extension rate. Some islands east of Japan may yield total velocity measurements of about 11 cm/year.

Short baseline opportunities using Madrid as a base station are obviously not as good since the rates in the local area are relatively smaller. Subcentimeter accuracies may become a reality as the VLBI technique matures, thus allowing the less dramatic crustal motions to be detected in time periods of a few years. Using Madrid as an intercontinental site shows some interesting opportunities with respect to total velocities on the Indian plate (~5 cm/year in Australia) and Pacific plate (~8 cm/year in Hawaii). Using a Madrid/Goldstone interferometer may yield baseline extension rate measurements on the order of 2 cm/year.

Goldstone as a base station has interesting opportunities for measurement of crustal plate drift using portable stations on various islands on the Pacific plate, and the Indian plate (Australia and vicinity). Here movement is on the order of 6 to 9 cm/year. A Goldstone/Hawaiian interferometer may measure a 2.5-cm/year extension rate.

Short baseline opportunities using Goldstone as a base station are excellent owing to the close proximity of the Pacific plate. Short baseline experiments using Goldstone as a base station have actually been carried out. The next section describes the results.

V. Present Measurements (Project ARIES)

Project ARIES currently operates the only sophisticated transportable VLBI system in the world, monitoring various baselines in California. The idea of using portable antennas to monitor a tectonically active and complex region such as California has been presented by Shapiro and Knight (Ref. 9). Project ARIES has been taking data since 1973, occupying various sites on the western side of the San Andreas fault (Pacific Plate) while the DSN stations at Goldstone and the Owens Valley Radio Observatory (OVRO) served as the larger fixed base stations on the North American plate side.

California is a tectonically complex region where the San Andreas fault serves as the principal plate boundary. Near the boundary each plate actually consists of many blocks, each behaving differently, hence the need for occupying many different sites in order to understand the tectonics of the region.

The current accuracy with which an ARIES vector baseline can be determined is at the 6- to 10-cm level (one sigma) in each of three orthogonal components. The accuracy of the baseline length is at the 3-cm level. Since plate motion per year is at approximately the same magnitude as the error level, detection of continuous movement is possible after a few years of data taking. The number of years of data taking for detection of plate drift depends on frequency of measurement and individual measurement error. The only site (baseline) occupied by the ARIES portable 9-meter antenna in which enough data has been taken and movement apparently detected is the JPL site (DSS 14/JPL baseline).

Figures 10-12 show the local California area displaying the Minster model results, using DSS 14 at Goldstone as a base station. The ARIES JPL location is also shown. The model predicts that the DSS 14/JPL interferometer should detect a

5.5-cm/year total velocity magnitude, a −1.0-cm/year baseline extension rate, (or +1.0-cm/year baseline compression rate) and a 5.4-cm/year transverse velocity magnitude, all consistent with the right lateral strike slip motion along the San Andreas fault, which separates the North American and Pacific plates. Transforming the model results to the usual geographic directions, one then predicts that JPL should move 3.6 cm/year west and 4.1 cm/year north, with respect to Goldstone. To date the only component of movement detected from VLBI that is statistically significant is a 5.6 ±1.9-cm/year westward movement of JPL relative to Goldstone (DSS 14) (Ref. 6). This rate was measured by the ARIES group utilizing data from VLBI experiments performed during the period 1974-1977. The measured rate is in reasonable agreement with the predicted 3.6 cm/year westward rate, but it is cautioned that it is not necessary for local measurements to match the general plate motion model, due to the complexities of plate tectonics previously discussed.

Project ARIES is a current research and development VLBI project. The operational version of ARIES, now in the design stages, is project ORION (Operational Radio Interferometry Observing Network), which will utilize a network of many portable stations. In addition to extragalactic radio sources, satellites may prove to be a valuable emitter of radio signals for application to VLBI. A future variation of the ARIES technique is the newly initiated project SERIES (Satellite Emission Radio Interferometric Earth Surveying). This technique will make use of military satellites as sources instead of natural radio sources. Because the artificial satellites have higher received signal-to-noise ratios than natural radio sources, this technique has the advantage of utilizing less sophisticated ground equipment.

VI. Conclusion

VLBI provides an excellent tool for measuring crustal movements and deformation by judicious placement of antennas on various sites within plates and across plate boundaries. Measurement of crustal movement will confirm the theory of plate tectonics, and measurement of deformations may yield valuable information regarding the structure of the plates. Thus, we will be able to get an improved picture of local deformations, and be able to see what type of behavior is occurring as a function of time. Many measurements over the course of a year can give us increased time resolution. Important geodetic information can be obtained by combining results from both short (local) and long (intercontinental) baselines. As the VLBI technique is perfected, the accuracy in measuring baselines has the potential of reaching the subcentimeter level.

Acknowledgments

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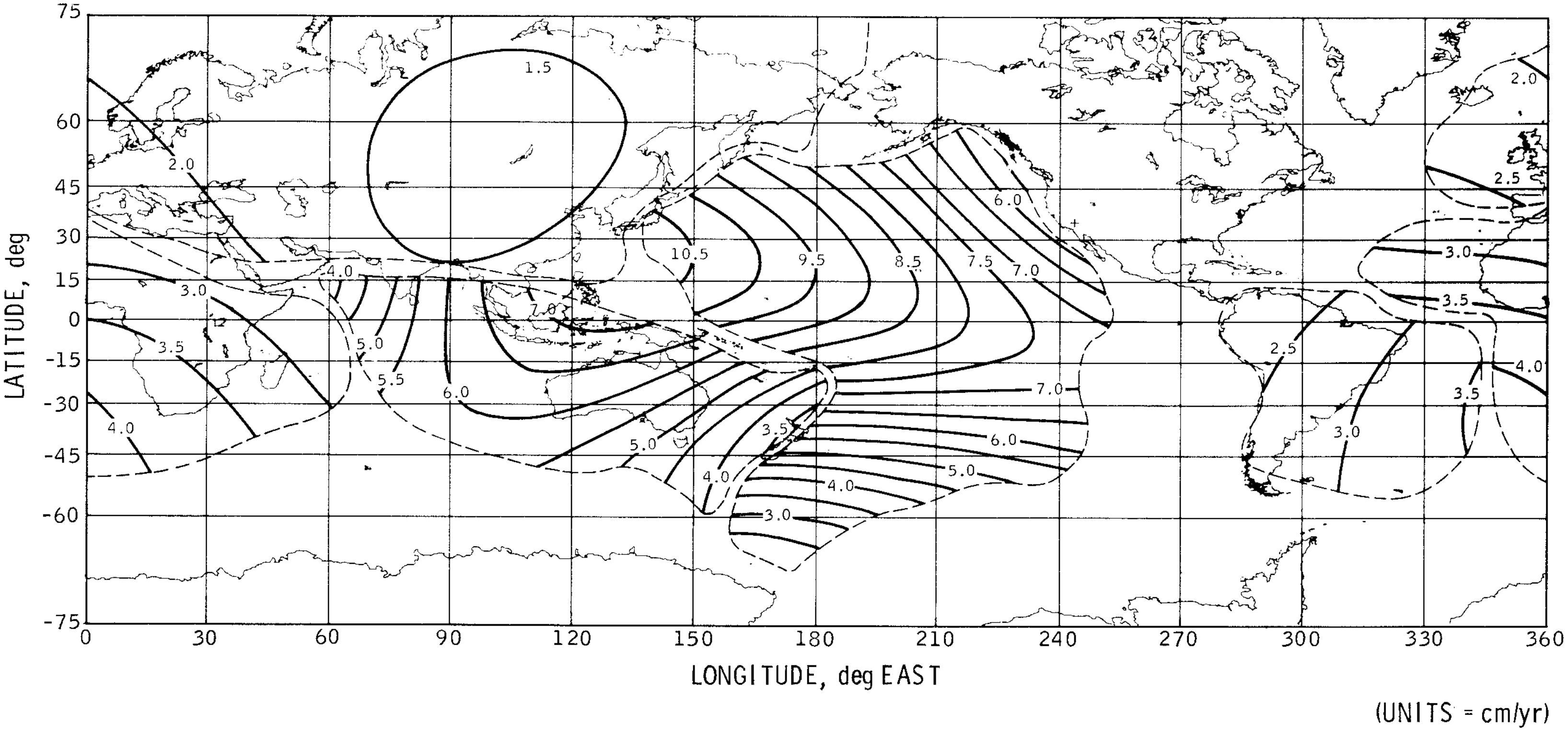

Fig. 1. Tectonic plate total velocities with respect to Goldstone

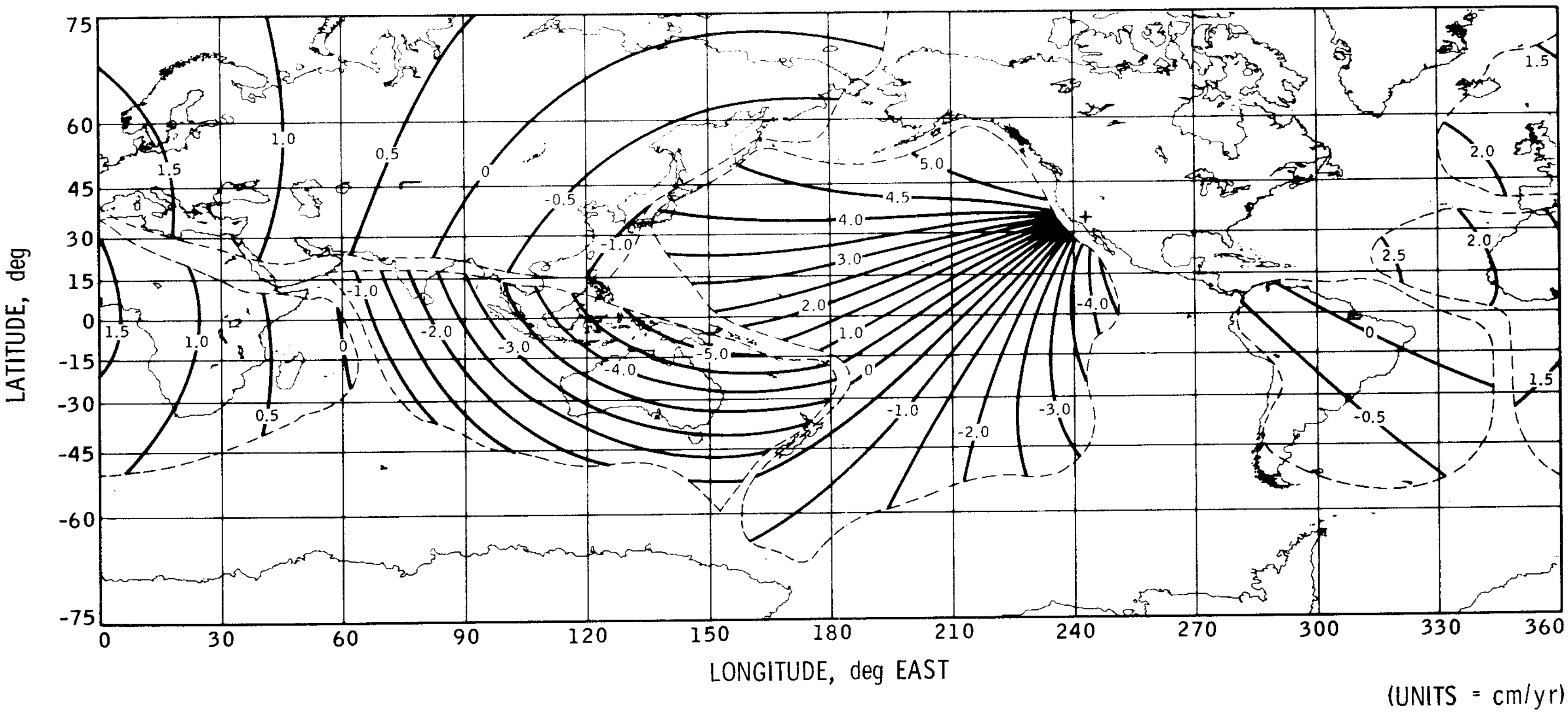

Fig. 2. Tectonic plate extension rates with respect to Goldstone

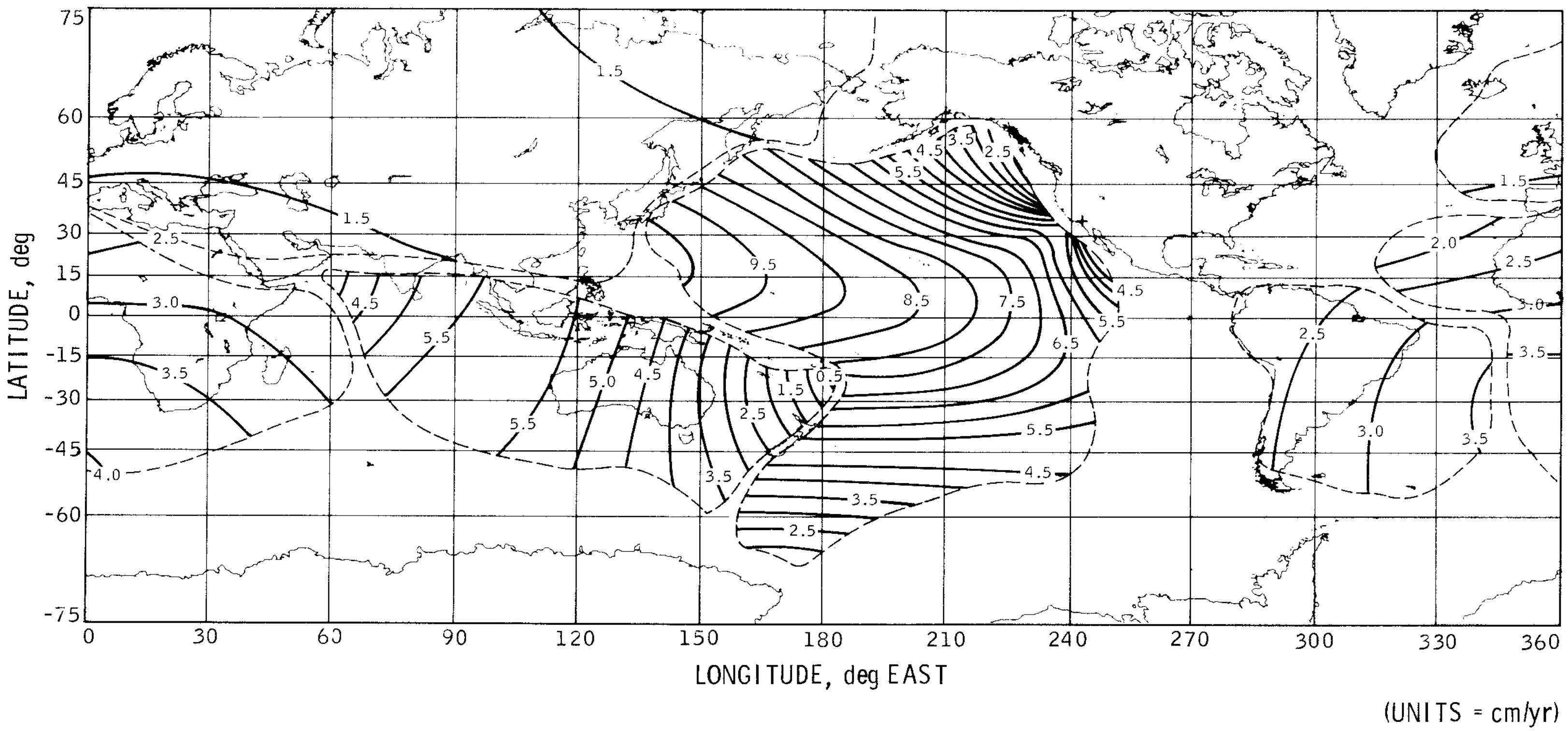

Fig. 3. Tectonic plate transverse velocities with respect to Goldstone

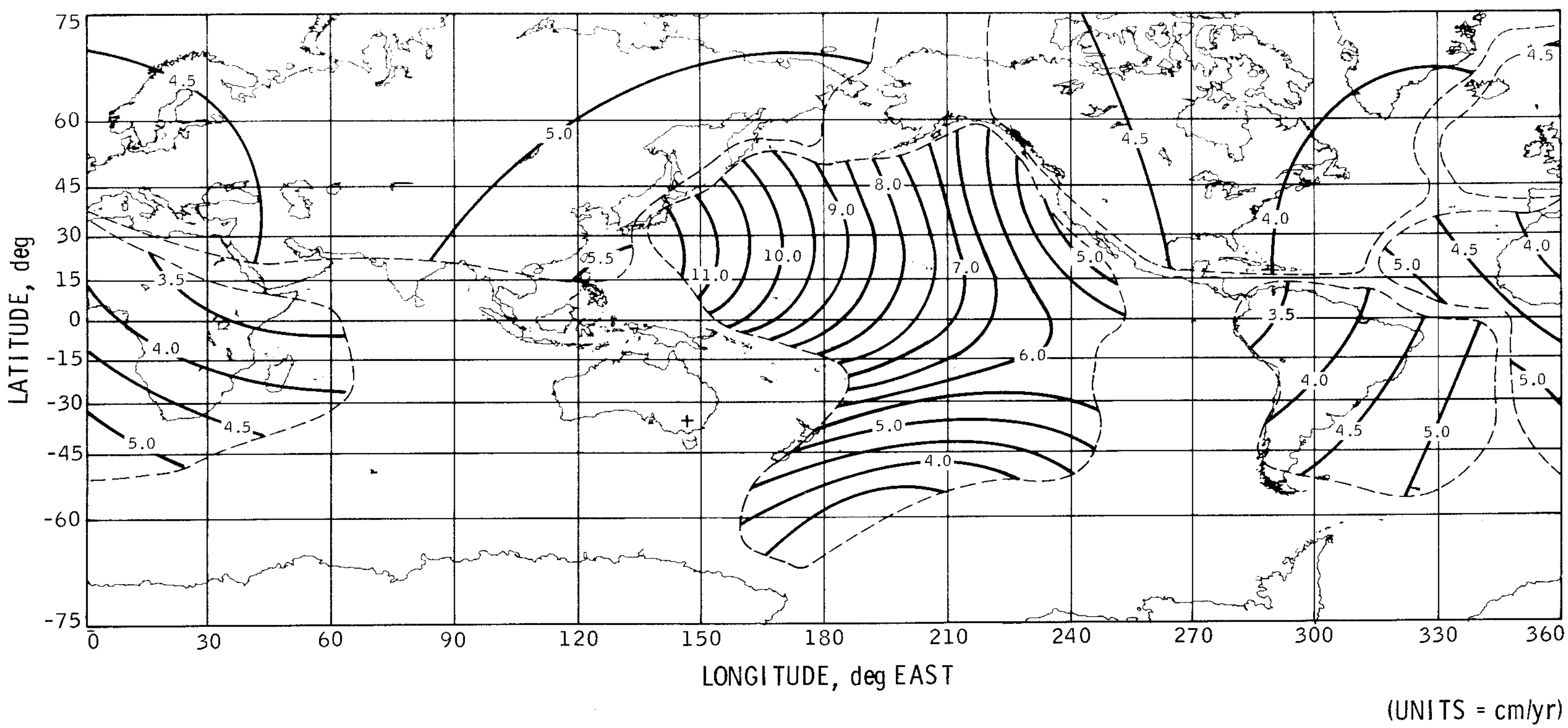

Fig. 4. Tectonic plate total velocities with respect to Canberra

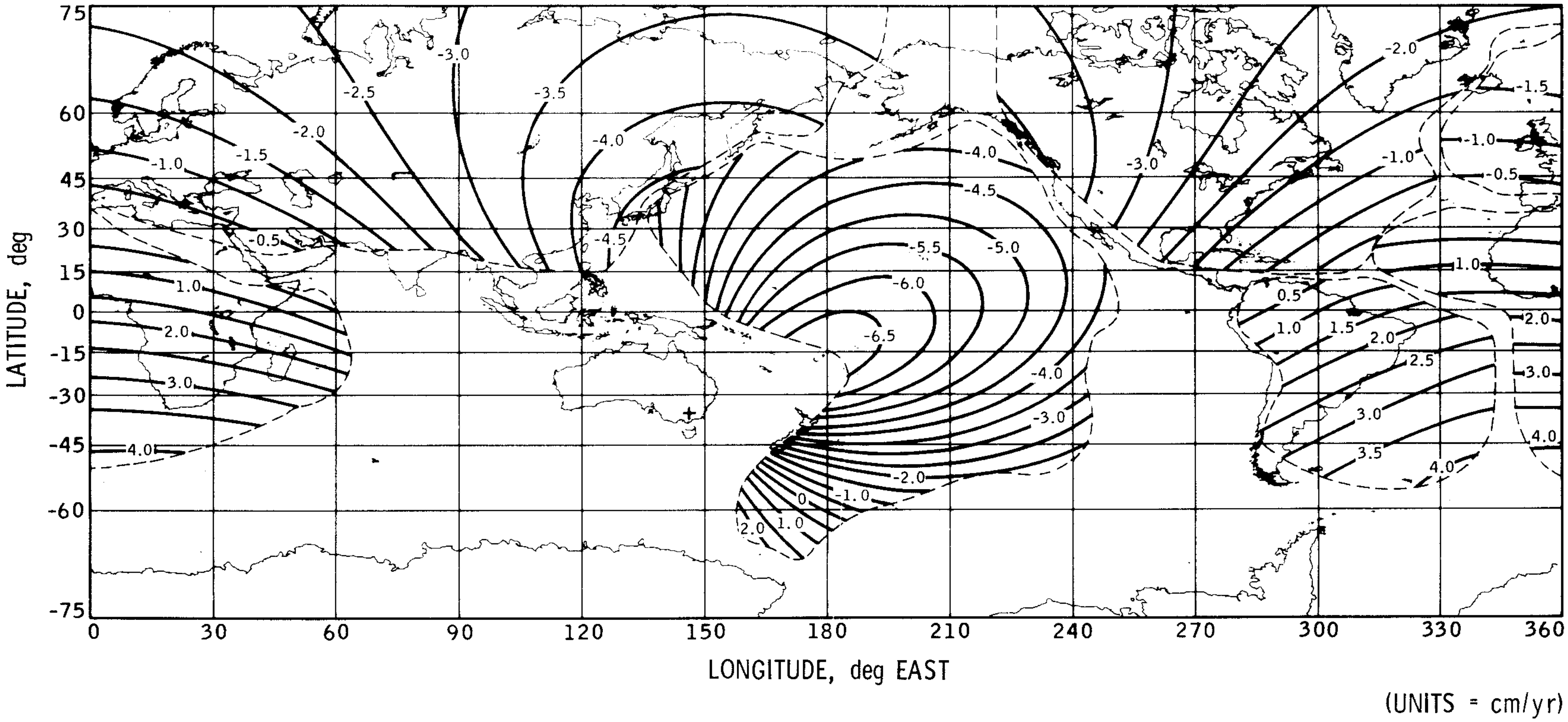

Fig. 5. Tectonic plate extension rates with respect to Canberra

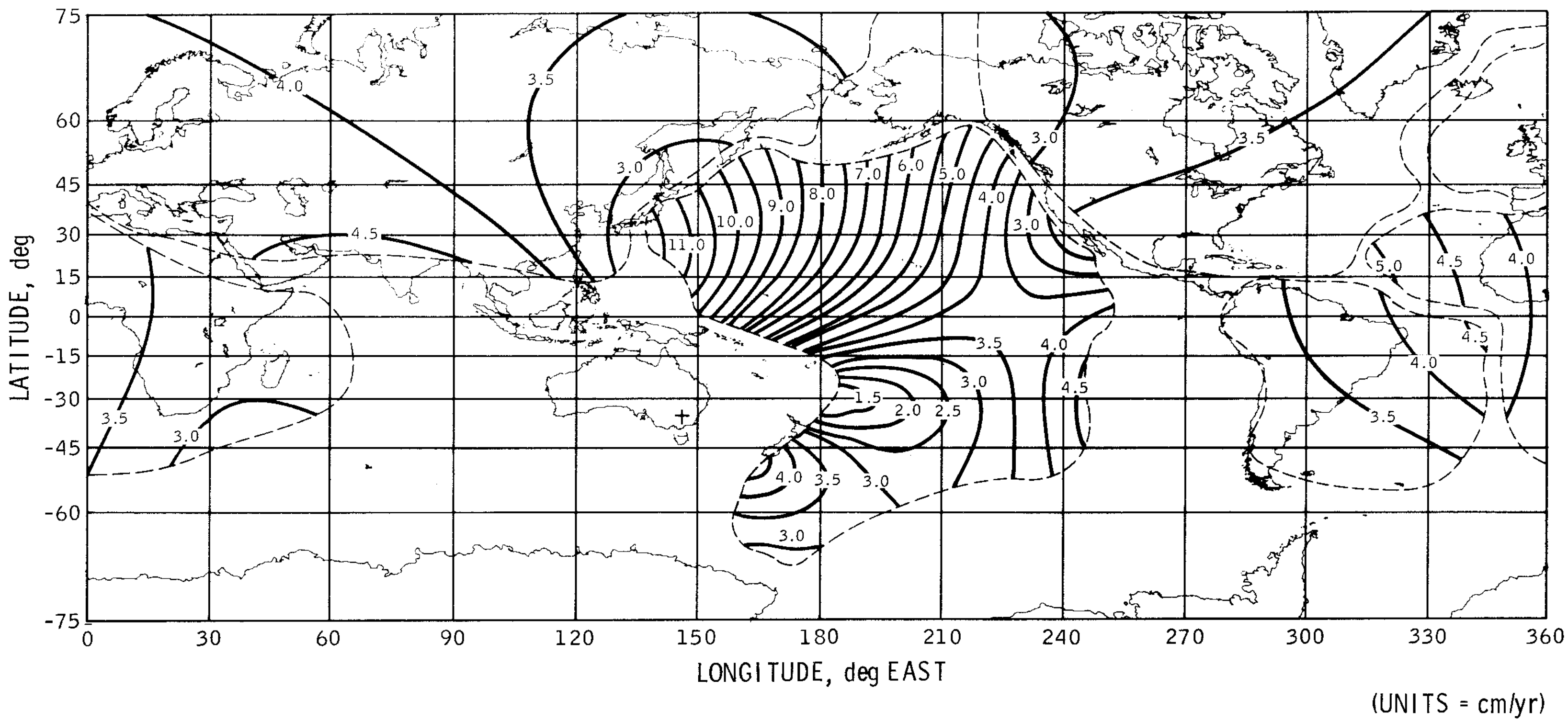

Fig. 6. Tectonic plate transverse velocities with respect to Canberra

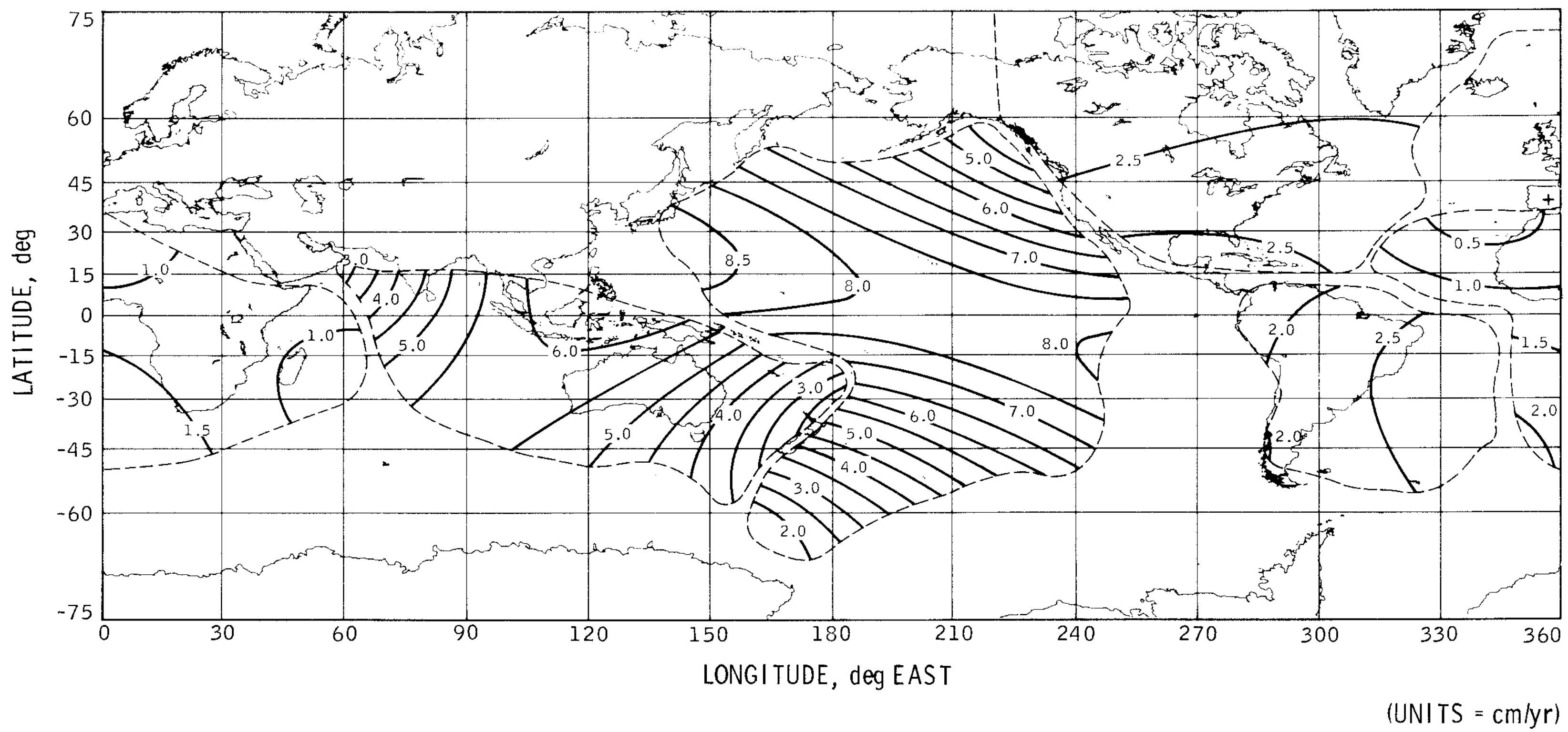

Fig. 7. Tectonic plate total velocities with respect to Madrid

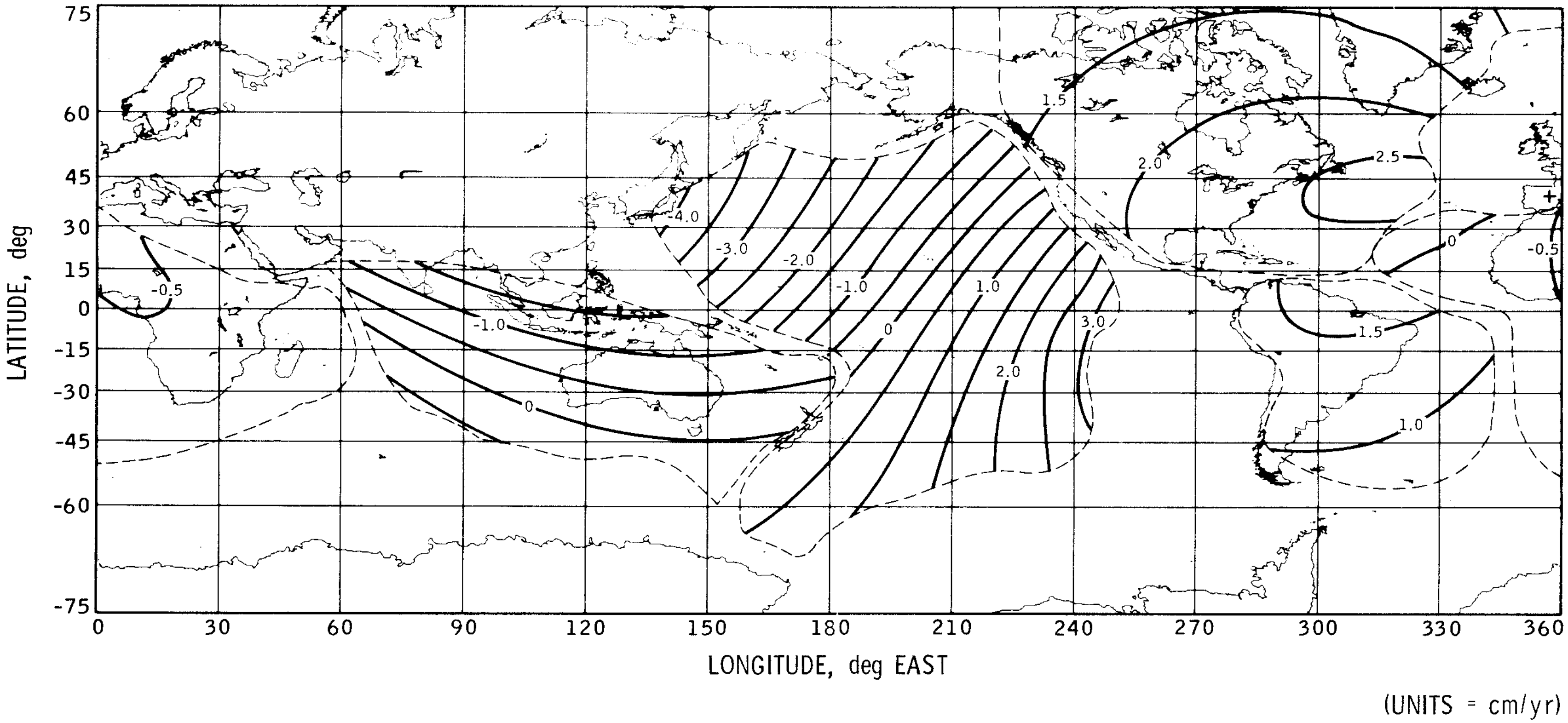

Fig. 8. Tectonic plate extension rates with respect to Madrid

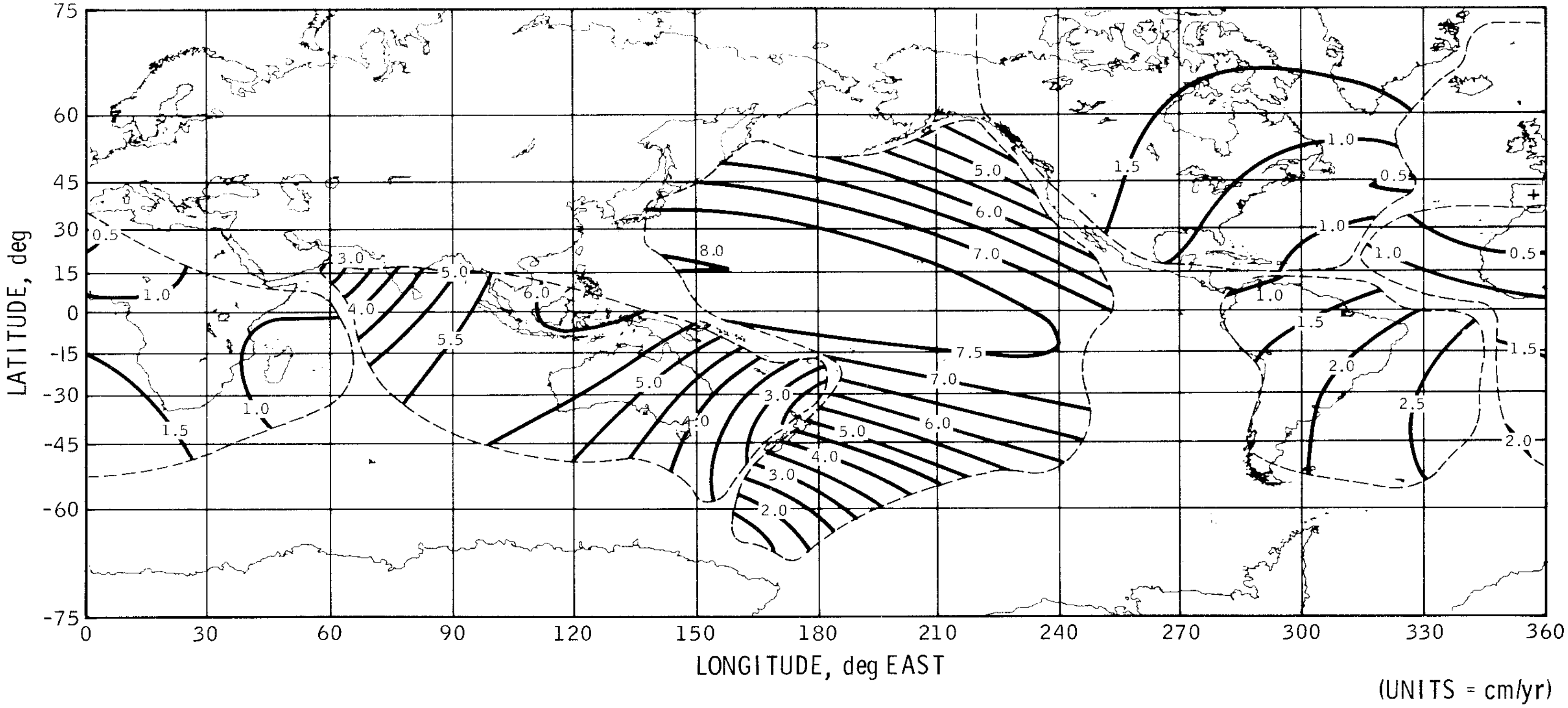

Fig. 9. Tectonic plate transverse velocities with respect to Madrid

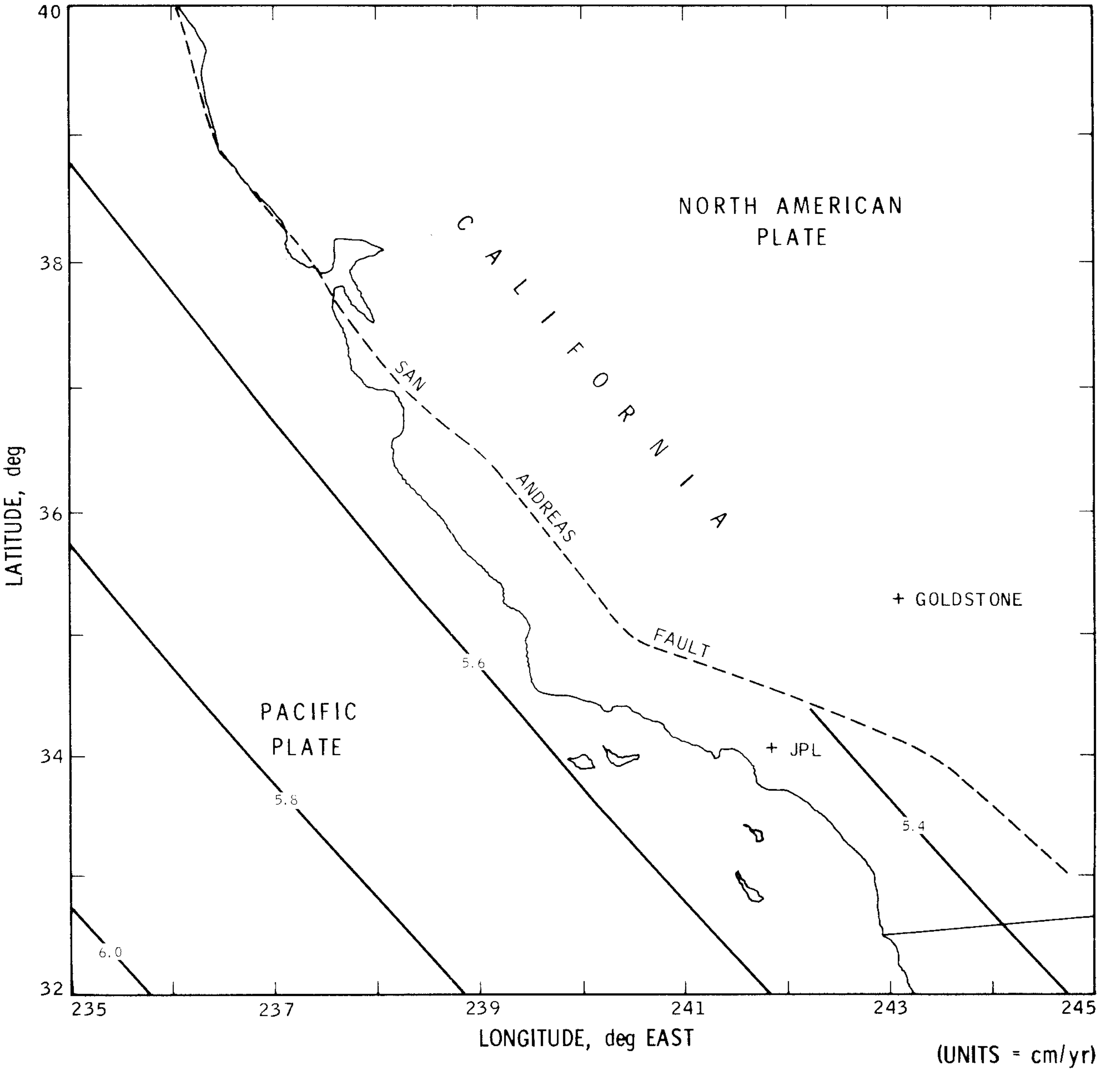

Fig. 10. Local plate total velocities with respect to Goldstone

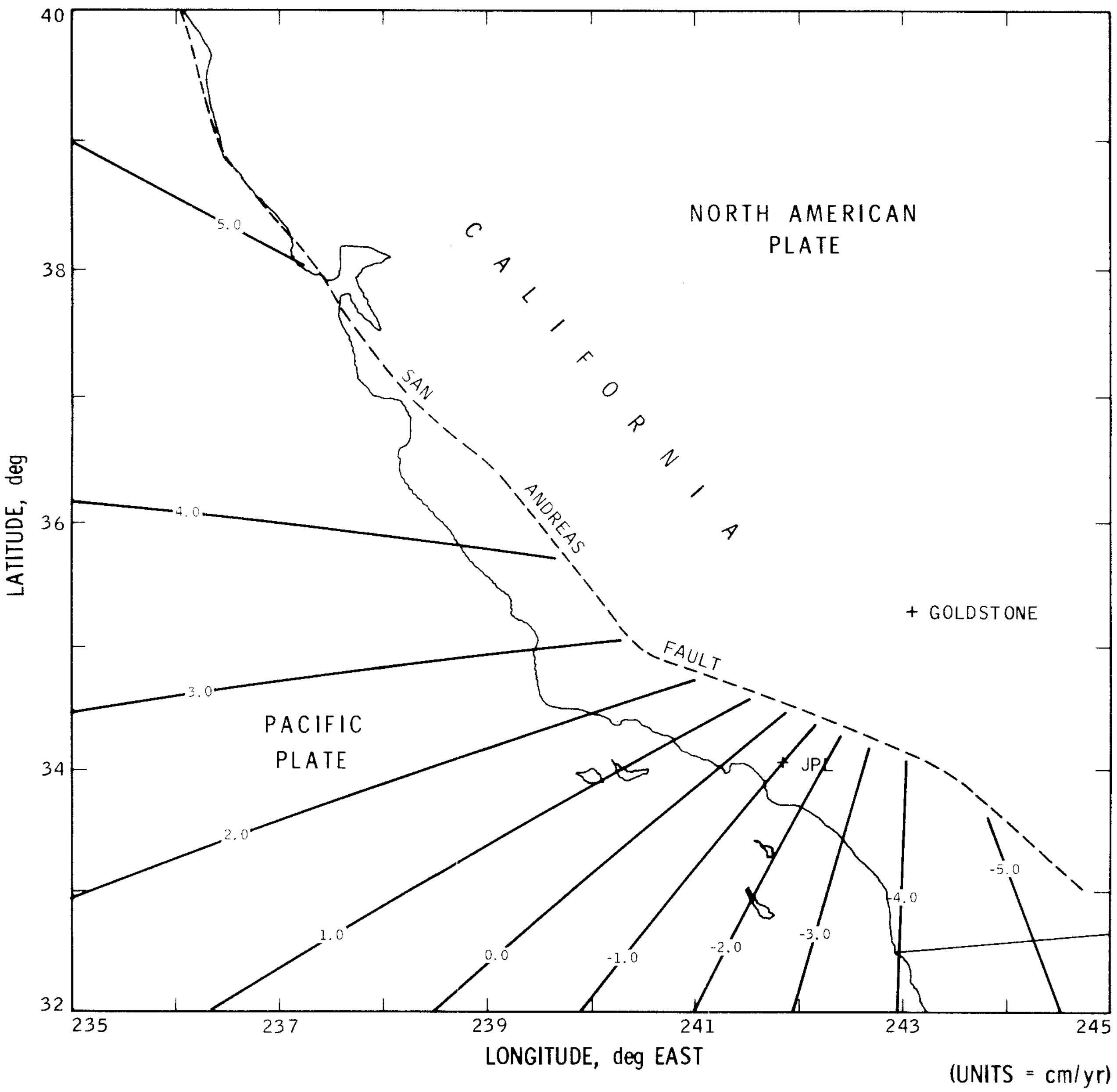

Fig. 11. Local plate extension rates with respect to Goldstone

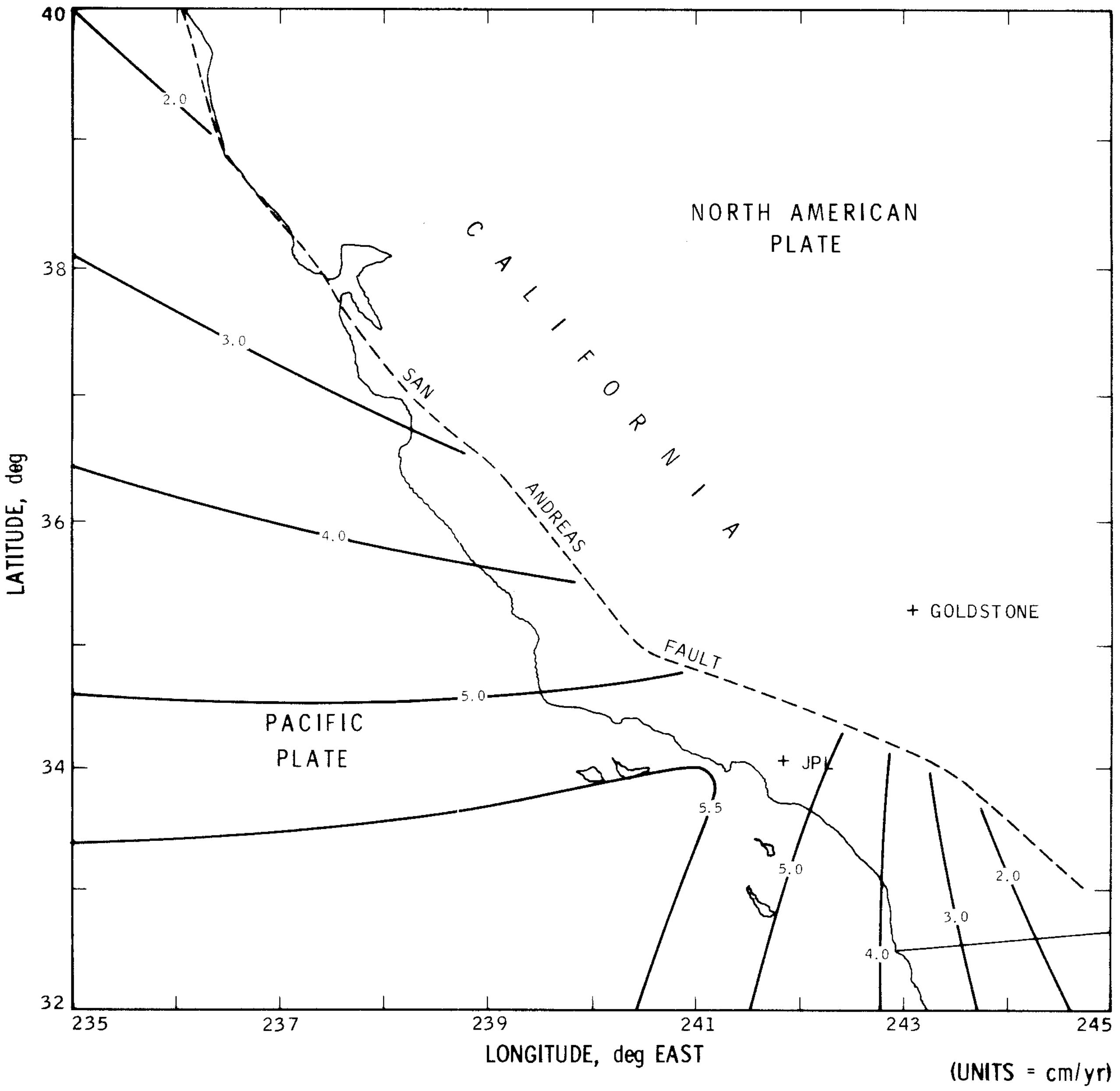

Fig. 12. Local plate transverse velocities with respect to Goldstone