Plate Dynamics near Boundaries: What Governs the Transition between Episodic and Continuous Motions?

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Abstract. International geodetic Very Long Baseline Interferometry observations have revealed that the bulk of a tectonic plate moves continuously at a rate consistent with the geologic average. On the other hand, movements are highly episodic at plate boundaries such as subduction zones and mid-oceanic ridges. The gap between these two different modes is bridged by the post-episodic slow diffusion of the stress toward the plate interior. The width of a transition zone is controlled by the episode recurrence interval and the stress diffusivity. Inter-episodic crustal deformation near plate boundaries come from such cyclic elastic deformation overprinted by a smaller amount of intraplate permanent deformation.

1. Introduction

Movements of tectonic plates, as slow as a few cm per year, bring continental drifts, interplate earthquakes, volcanisms in island arcs and mid-oceanic ridges, and many other phenomena. Their rates can be observed through two different time windows; a geological time window, a few millions of years wide, and a geodetic time window, a few or a few tens of years wide.

Geologic methods rely on the vast length of time with which the consequences of movements accumulate; a visible signature should be left after a long time no matter how slow the movement is. A good example is the present distance between Africa and South America, now apart by ~3000 km. Various geologic (e.g. paleomagnetic, paleontological) evidences suggest that they split from a single block ~135 million years ago. From this we can infer that the averaged spreading rate of the Atlantic Ocean has been 2–3 cm/year.

A more sophisticated geologic method utilizes ocean magnetic anomaly lin- eations created by geomagnetic field reversals. By correlating the anomaly patterns with the reversal history established on land by paleomagnetic and geochronological studies, we can estimate how much a new ocean floor has spread during the last few millions of years. These data, along with transform fault strikes and interplate earthquake slip directions, are distilled into “current plate motion models” where the plate movements are expressed in terms of the Euler pole positions and rotation rates about them. NUVEL 1 model (DEMETs et al., 1990) obtained in this way can give an accurate velocity of a plate at any point as an average over the last few millions of years.
Fig. 1. Observed minus predicted velocity vectors of world-wide VLBI stations with their one-sigma error ellipses. Squares show 15 reference points used to fit observed vectors to NUVEL1 predictions. Their residuals are magnified in the inset.
Geodetic methods rely on their accuracy; if distance measurements between points on different plates are accurate to a few cm, we can detect their movements in a few years. Developments of space geodetic techniques such as Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR) and Global Positioning System (GPS) and international cooperations in the last decade enabled us to observe the plate movements through this new time window. It also offers a rare chance to study how different the same phenomenon looks like through time windows with widths as different as 10^6.

2. Predicted and Observed Velocities

In this study, I let the VLBI data represent the observations through a geodetic window and examine their coincidence with the NUVEL1 model. The Goddard Space Flight Center annually issues the results of geodetic VLBI measurements in which they give the velocity vectors of all the VLBI stations estimated in a solution obtained combining all the group delay data then available. The last issue (Ryan et al., 1993) gives a set of velocity vectors which best explains the delay data obtained 1979–1991.

In order to estimate absolute station velocities using VLBI, essentially a relative positioning technique, they constrain six velocity components; the horizontal velocity vector of the Westford (Massachusetts) and the azimuthal change of the Richmond (Florida) viewed from Westford are fixed to those predicted by the non-net-rotation(nnr)-NUVEL1 model (Argus and Gordon, 1991) and the vertical velocities of the Westford, Richmond and Kauai (Hawaii) were fixed to zero. To this type of solution (a solution obtained with a minimum of possible constraints), we can add any small arbitrary translation (bias) and/or rotation without losing its property as a solution which best explains the observed delays in a least-squares sense (Fallon and Dilling, 1992) (although adding a rotation modifies the secular change of the Earth’s rotation parameters). Here I estimate the rotation and translation that should be added to this set of vectors in order to minimize the differences (from the nnr-NUVEL1 predictions) of not only Westford, Richmond and Kauai but also additional points globally distributed.

For this purpose we selected reference stations on the stable plate interiors which we define as the area more than 500 km distant from the nearest boundary. A smaller distance would increase the risk of the result being affected by plate deformations and too few stations would be left in the plate interiors with a larger threshold. We chose the following 15 fixed permanent VLBI stations (Fig. 1); six on the North American plate, i.e. Fairbanks (Alaska), Westford, Algonquin, Richmond, Maryland Point and Green Bank (all in the eastern North America), two on the Pacific plate, i.e. Kauai (Hawaii) and Kwajalein (Marshall Islands), four on the Eurasian plate, i.e. Wettzell (Germany), Effelsberg (Germany), Onsala (Sweden) and Madrid (Spain), two on the Australian plate, i.e. Canberra (Australia) and Hobart (Tasmania) and Hartebeesthoek (South Africa) on the African plate. The Shanghai VLBI station, China was excluded although it is more than 500 km distant from the nearest known boundary (the next section explains why). The best set of the observed
vectors was obtained by rotating and translating the velocity set of Ryan et al. (1993) as a whole so that the vectors of the 15 reference points best coincide with the predictions in a weighted least-squares sense. Figure 1 shows the horizontal components of the residual vectors, namely differences between the “observations” obtained in this way and the nrt-NUVEL1 “predictions”.

3. Origin of the Differences

The residual vectors of the 15 reference stations are magnified in the inset of Fig. 1. No stations show discrepancies beyond 1 cm/year and their weighted-root-mean-square displacement is 0.85, 0.80 and 2.31 mm/year in the north-south, east-west and up-down components respectively. This implies that the internal errors of the NUVEL1 model and horizontal crustal movements other than plate tectonics, e.g. those caused by post-glacial isostatic rebound (James and Lambert, 1993), are not much more than 1 mm/year. It also demonstrates the consistency of the movements of the plate interiors between the two different time scales. Vectors of non-reference stations in Fig. 1 show the displacements of the points with respect to the interior of the plates on which the points are supposed to lie. They are often significant suggesting the deformation of plates near boundaries.

3.1 Movement of the Shanghai VLBI station

Shanghai’s east-southeastward displacement with respect to the Eurasian plate of ~1 cm/year (Fig. 1) is a good example showing the incompleteness of plate motion models. Ocean magnetic anomaly data suggest that the Indian subcontinent has moved northward by as much as 1500 km since it started to collide with Eurasia ~40 million years ago (Molnar and Tappin, 1975). India experienced little deformation after the collision suggesting that a certain amount of “room” was somehow created e.g. by north-south contraction on the Eurasian side, to allow such a large movement. Molnar and Tappin (1975) pointed out another possibility that large crustal blocks were extruded away one after another and interpreted huge strike-slip faults in the Tibetan plateau as the boundaries separating such crustal blocks. A block currently extruded spans from Tibet to southeast China, on whose easternmost edge lies the Shanghai VLBI station.

Numerical experiments (Houseman and England, 1993) based on a thin viscous sheet model of the lithosphere show that during collision the eastern boundary is smoothly displaced at a rate about a quarter of the indentation rate (i.e. the rate of the northward movement of India) with only minor variation due to geometry or rheology. The current velocity of India is ~5 cm/year and its quarter roughly agrees with the observed Shanghai’s velocity (Fig. 1).

3.2 Cyclic movement of points near plate boundaries

Smallness of the residual vectors of reference points (Fig. 1) demonstrates that the bulk of a plate moves continuously at a rate consistent with the geologic average. This makes a contrast with episodic movements of plate boundaries e.g. interplate earthquakes along subduction zones and transform faults, and rifting episodes along
mid-oceanic ridges. Residual vectors of points near plate boundaries (Fig. 1) may reflect the difference between these two modes. Generally speaking, a plate near its boundary moves in two stages, the first being the co-episodic elastic response of the lithosphere. If an underlying asthenosphere is of Maxwellian viscoelasticity, although surface deformation at \( t = +0 \) is that of an elastic half space, the strain field at \( t = \infty \) (when asthenospheric shear stresses decay to zero) should satisfy a two-dimensional plane-stress condition. Hence there should be the second stage, post-episodic slow propagation of the stress toward the plate interior.

Residual vectors in Fig. 1 are the most notable in subduction zones; points on arcs move landward (in the same direction as the subducting oceanic plates) with respect to the continental plate interiors. MA et al. (1990) and ARGUS and LYZENGA (1993) explained the deformations observed in Alaska and in Japan, respectively, by assuming “back-slip” in an “elastic half space” (SAVAGE, 1983). However, recurrence intervals of interplate earthquakes are usually much longer than the Maxwellian time constant of the asthenosphere, which suggests that an elastic half space is not appropriate to model interseismic plate dynamics near boundaries. In a word, the back-slip model considers only the first stage and neglects the time-dependent second stage. Development of a new model incorporating the time-dependent response of the lithosphere, similar to the one proposed by HEKI et al. (1993) for divergent boundaries, would be meaningful to understand interseismic crustal deformation in subduction zones.

3.3 Secular movement of points near plate boundaries

In addition to such cyclic deformation, there should be permanent deformation due to the brittle fracture (active faults) and/or the ductile flow (active folds) of the thin island arc lithosphere (HEKI et al., 1990). Deformation rate of arcs inferred from geologic observations such as the rates of slip on Quaternary intraplate faults gives an estimate of this kind of deformation. Such a “geological” deformation rate should be significantly smaller than the deformation rate observed by geodetic surveys because the large portion of “geodetic” deformation will be recovered by the next interplate earthquake.

REFERENCES


