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THE NAZCA-SOUTH AMERICA CONVERGENCE RATE AND THE RECURRENCE OF THE GREAT 1960 CHILEAN EARTHQUAKE

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Abstract. The seismic slip rate along the Chile Trench estimated from the slip in the great 1960 earthquake and the recurrence history of major earthquakes has been interpreted as consistent with the subduction rate of the Nazca plate beneath South America. The convergence rate, estimated from global relative plate motion models, depends significantly on closure of the Nazca - Antarctica - South America circuit. NUVEL-1, a new plate motion model which incorporates recently determined spreading rates on the Chile Rise, shows that the average convergence rate over the last three million years is slower than previously estimated. If this time-averaged convergence rate provides an appropriate upper bound for the seismic slip rate, either the characteristic Chilean subduction earthquake is smaller than the 1960 event, the average recurrence interval is greater than observed in the last 400 years, or both. These observations bear out the nonuniformity of plate motions on various time scales, the variability in characteristic subduction zone earthquake size, and the limitations of recurrence time estimates.

Introduction

The May 22, 1960 Chilean earthquake, reflecting the subduction of the Nazca Plate beneath South America, is the largest earthquake ever instrumentally recorded and the type example of a great subduction zone earthquake. In the first determination of fault dimensions from instrumental data, Benioff et al. [1961] used pendulum seismograph records to estimate the fault length (dimension along strike) as 960-1280 km. In a later study, Plafker [1972] used the distribution of aftershocks and surface deformation to estimate that approximately 20 m of thrust faulting occurred on a fault approximately 1000 km long and about 120 km wide (downdip dimension). Kanamori and Cipar [1974] showed that the focal mechanism inferred from a long period strain seismogram was consistent with Plafker's fault geometry and that indicated by the aftershock distribution [Stauder, 1973]. For this geometry, they estimated the seismic moment as 2.7×10^{30} dyne-cm, which yields a slip of 24 m, assuming a fault length of 800 km and a width of 200 km, consistent with the aftershock area. Historical records [Lomnitz, 1970] summarized by Kelleher [1972] indicate that previous large earthquakes occurred in this segment of the trench (approximately 37°-43°S) in 1837, 1737 and 1575, for an average recurrence of 128±31 years.

Kanamori [1977] compared the slip rate estimated from the seismic moment release in interplate thrust fault earthquakes to that predicted by relative plate motions for various subduction zones. As almost all seismic slip occurs in the largest events, the variation in seismic slip fraction is essentially equivalent to the variation in the size of the largest interplate thrust events. Assuming that 24±7 m slip occurred in the 1960 Chilean earthquake, and that such earthquakes occur every 130±30 years, the seismic slip rate would be 18.5 cm/yr; the range corresponding to the assigned uncertainties would be 31 to 10.6 cm/yr. As global plate motion model RM1 [Minster et al., 1974] predicted a Nazca-South America convergence rate of 11 cm/yr, within the range allowed by the slip and recurrence time values given the assigned uncertainties (Figure 1), Kanamori concluded that the seismic slip rate corresponded to the entire plate motion. This region would thus be one limiting case in a continuum. Seismic slip fractions range from approximately 100% in this area and that of the great 1964 Alaskan earthquake, 40-25% in the Kuriles [Kanamori, 1977; Seno and Eguchi, 1983], 15-10% in the Lesser Antilles [Stein et al., 1986], to essentially zero (no large plate boundary thrust events) in the Marianas [Kanamori, 1977; Seno and Eguchi, 1983].

The fraction of seismic slip is a significant parameter for several purposes. The earthquake hazard at a subduction zone depends on the seismic slip rate rather than the total convergence rate. The variation in seismic slip fraction between subduction zones may also reflect the mechanics and dynamics of convergence. Kanamori [1977] proposed that the seismic slip fraction and the size of the largest thrust events reflect the degree of mechanical coupling at the plate interface. Ruff and Kanamori [1980] showed that these effects correlate with the convergence rate and age of the subducting lithosphere, the two key parameters in subduction zone dynamics [McKenzie, 1969] which may also

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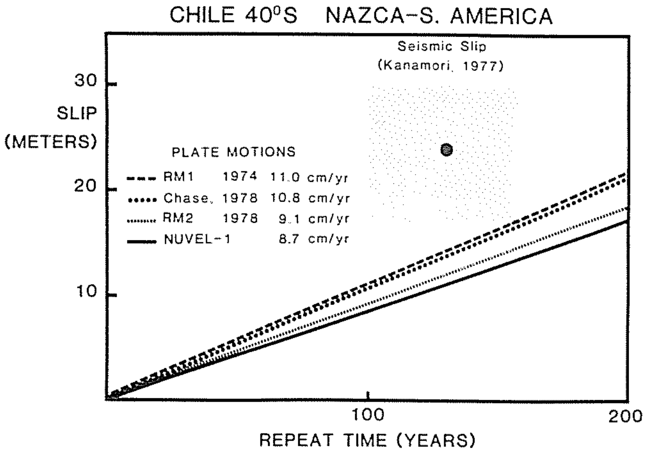

Fig. 1. Comparison of seismic slip rate and plate motions at the Nazca-South America subduction zone. Shaded region indicates slip in the 1960 Chilean earthquake and recurrence rate of large trench events in the last 400 years with estimated uncertainties [Kanamori, 1977]. Lines indicates convergence rates at 40°S, 74°W predicted by different relative plate motion models. The Euler vectors are listed in Table 1.

control the stress state in the subducting plate [Fujita and Kanamori, 1981]. For example, old lithosphere subducting slowly, as in the Lesser Antilles, would be poorly coupled; the Chilean area, with young lithosphere subducting rapidly, would be strongly coupled. It has been further suggested [Lay and Kanamori, 1981] that the mechanical nature of the interface may be reflected in asperities which control the rupture complexity of interplate thrust earthquakes.

Plate Motions

We have recently reanalyzed the rate of Nazca-South America motion as part of development of a new global relative plate motion model, NUVEL-1 [DeMets et al., 1985; 1986 in prep.]. The model, based on a larger dataset than the earlier models, incorporates data that has subsequently become available. As shown in Figure 1, the convergence rate we obtain at the location of the 1960 event, 8.7±0.3 cm/yr, is lower than earlier estimates.

As convergence rates are used to estimate seismic slip fractions and recurrence times, it is natural to ask whether the 20% variation in slip rate between different models indicates only the uncertainty in the determination. This appears not to be the case. Estimates of plate motions and the fit to the global dataset have been improving as successive models incorporate additional and better data and boundary configurations are better known [DeMets et al., 1986 in prep.]. For example, when Chases's [1972] model was developed, the data were inadequate to resolve separate North and South American plates; later models (RM1 [Minster et al., 1974], that of Chase [1978], RM2 [Minster and Jordan, 1978], and NUVEL-1) have both. The consequences for the Chile Trench are shown in Figure 1 by the predictions of subsequent models. The predicted convergence rate is highest for RM1 and decreases with successively more recent models.

This effect results simply from the geometry of relative plate motions. The data used in such models are rates derived from magnetic anomalies at midocean ridges, and azimuths from transform directions and earthquake slip vectors. An inversion is conducted to find the set of Euler vectors that provide the best fit to all the data in a least squares sense [Chase, 1972; Minster et al., 1974]. As no rate data are available at subduction zones, the predicted motion is derived from closure, assuming plates are rigid. The predicted Nazca-South America convergence rate thus depends on data from other boundaries and reflects their uncertainties. As better data become available on these boundaries, the estimate of the convergence rate improves. Since closure of the global circuit is required, each datum affects the model, as described by the importance matrix [Minster et al., 1974]. This idea is illustrated graphically in Figure 2, which shows the plates, boundaries, and data types used in NUVEL-1. The Nazca-South America rate is controlled by a number of circuits for which rate data exists, the shortest and most direct being Nazca - Antarctica - South America. An number of alternative, more indirect circuits, including NZ-AN-AF-SA, NZ-PA-NA-AF-SA and NZ-AN-AU-AF-SA, also contribute to the solution.

One important feature of NUVEL-1 is an improved dataset for Nazca-Antarctica motion compared to RM1, the Chase [1978] model, or RM2. Additional azimuthal data on the Chile Fracture Zone (more properly the Chile Transform) is provided by slip vectors [Engeln, 1985] and bathymetric data [Anderson-Fontana et al., 1986 in prep.]. Most significantly, new rate data are used. The only prior rate came from a single profile across the Chile Ridge [Klitgord et al., 1973] which suggested an average rate of about 80 mm/yr over the last five million years. Herron et al. [1981] analyzed profiles across a number of ridge segments, and showed that spreading has slowed to an average rate over the last three million years (anomaly 2′) of about 64 mm/yr. NUVEL-1, which includes these data, thus predicts

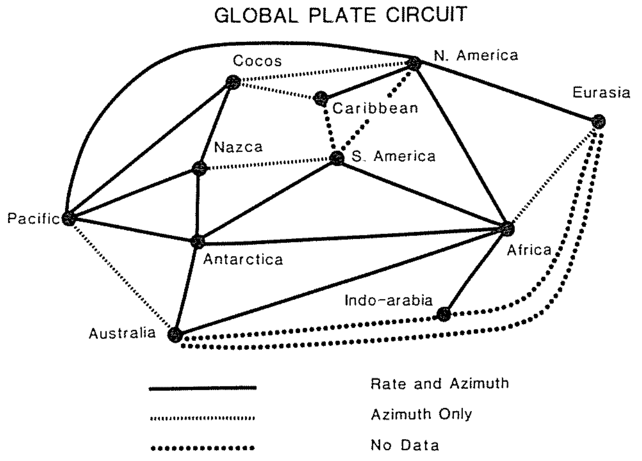

Fig. 2. Plate circuits used in NUVEL-1 [DeMets et al., 1986 in prep.]. Lines indicate boundaries and show whether rate and azimuthal data, azimuthal data alone, or none, are used. Convergence rates at subduction zones, where only azimuthal data are available, are inferred by closure.

Table 1. Nazca - South America Euler Vectors

model	latitude (°N)	longitude (°W)	rate (deg/my)
RM1	51.9	91.4	.99
Chase [1978]	48.6	90.2	.98
RM2	59.1	94.7	.84
NUVEL-1	53.9	94.5	.79

slower Nazca-Antarctica spreading and hence slower Nazca-South America convergence. (The time scale used here is that of Harland et al. [1982]; anomaly 2′ corresponds to 2.48-3.4 Ma).

The more rapid convergence predicted by RM1 and the Chase [1978] model results from the faster Chile Rise spreading rate. Although this rate is included in RM2, RM2 predicts slower Nazca-South America convergence than RM1 and the data. Minster and Jordan [1978] noted this and showed that it resulted from new data on the Cocos-Nazca and Nazca-Pacific spreading centers. Their prediction, based on closure (Figure 2), is supported by the recent Nazca-Antarctica rate data.

Seismic Slip Rate Implications

If the plate motion averaged over several million years provides an appropriate upper bound on the time averaged seismic slip rate, the seismic slip rate must be significantly lower than estimated by Kanamori [1977]. This observation, of course, reinforces his argument that all slip occurs seismically. That slip rate was estimated from 24 m slip in the 1960 earthquake and a 130 year recurrence time for the last 400 years. These slip and repeat time values cannot both be representative of the plate motion. This discrepancy can have several causes. The 1960 slip, derived from seismic moment and fault dimension estimates [Kanamori and Cipar, 1974], might be inaccurate given that only one record was available for analysis; the agreement with Plafker's [1972] value argues against this possibility. Furthermore, a recent study by Cifuentes and Silver [1986] yields similar moment and fault length estimates.

The simplest interpretation is that the 1960 slip and repeat time values are correct but simply unrepresentative of the long term convergence averaged over the approximately three million years that the plate motion models reflect. On the average such earthquakes must occur less frequently and/or have smaller slip. There is a simple tradeoff shown by the extremes for an 8.7 cm/yr rate; earthquakes with 24 m slip can occur only every 275 years, or earthquakes occur every 130 years but have average slip 11 m. Nishenko [1985] noted this discrepancy between recurrence times from historical seismicity and that expected from the plate motion using the RM2 rate; the effect is even stronger using NUVEL-1.

It thus seems likely that the 1960 earthquake was larger than the characteristic Chilean subduction event. Such variations have been observed elsewhere. It has been known for some time that different segments of a subduction zone can rupture either simultaneously or as a series of earthquakes [Ando, 1975]. More recently, it has been recognized that the net slip can vary. Kanamori and McNally [1982] find that three earthquakes since 1942, which together ruptured a segment of the subduction zone along the Colombia - Ecuador coast which broke in 1906, have only about 20% of the moment and 50% of the slip that occurred in 1906.

Such analysis is more difficult for the area of the 1960 Chilean earthquake since the previous large earthquake, in 1837, predates instrumental seismology. Tsunami data suggest a somewhat smaller moment for the 1837 earthquake than the 1960 event; Abe [1979] and Nishenko [1985] obtain moments approximately 60% of the 1960 moment. The fault also seems to have been shorter; cultural records [Lomnitz, 1970] are interpreted as indicating a fault length 50% [Kelleher, 1972] to 75% [Nishenko, 1985] of that for 1960. Comparison of displacements is even more difficult, as it depends on the quotient of moment and fault length and requires an assumption about fault width scaling. As a result, the uncertainties allow for either larger or smaller displacements in the 1837 earthquake. Sykes and Quittmeyer [1981] and Nishenko [1985] assumed the same width (so that displacements scale inversely with length) and proposed that the 1837 slip was about 50-75% that of the 1960 event. Such smaller slip values are also suggested by the plate motions.

The Chilean situation demonstrates the common but frustrating difficulties in comparing seismic slip rates to plate motions even when the plate motion is adequately known and the seismic slip estimates seem reasonable. Seismic slip deficiencies and excesses have different consequences. An apparent large aseismic slip fraction is ambiguous because it can result from either aseismic subduction or a time sample that is unrepresentative, either intrinsically or due to an incomplete record. In contrast, excess seismic slip requires that the time sample be in some way unrepresentative of long term plate motions.

These observations indicate the nonuniformity of plate motions on different time scales. Plate motions averaged over a few hundred years can differ from those averaged over a few million years. Similarly, the earthquake data suggest that plate motion can be nonuniform on a scale of a few hundred years. Moreover, plate motions in the last million years can differ from those averaged over several million years [Vogt, 1986]. In particular, Herron et al. [1981] note that the spreading rate on the Chile Rise averaged over the central anomaly (730,000 years) is 56 mm/yr, less than the 64 mm/yr average over the last 3.4 million years. Nazca - South America convergence over the last million years may thus be even slower than 8.7 cm/yr. It is thus unclear which averaging intervals can be meaningfully compared. Space based geodetic techniques, which offer the most "instantaneous" data possible, should provide further insights on this issue.

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