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A reappraisal of seafloor spreading lineations in the Gulf of California: Implications for the transfer of Baja California to the Pacific plate and estimates of Pacific-North America motion

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Abstract. An analysis of seafloor spreading lineations in the southern Gulf of California demonstrates that divergence of the Baja peninsula from North America since 3.6 Ma has been significantly slower than Pacific-North America (PA-NA) motion estimated solely from closures of global plate circuits. This discrepancy remains unchanged or increases with modifications to the plate circuits and kinematic data used to predict PA-NA motion, suggesting that it arises from the probably-incorrect assumption that Baja California has been rigidly coupled to the Pacific plate since 3.6 Ma. A ~15% increase in seafloor spreading rates in the southern Gulf after ~1 Ma could have been caused by a transfer of motion along faults west of Baja California to the modern-day plate boundary, or alternatively could indicate a recent speedup in PA-NA motion. Both interpretations imply that PA-NA motion is now 4±2 mm yr^{-1} (2σ) faster than predicted by the 3.16-Myr-average NUVEL-1A model.

Introduction

Beginning at ~12 Ma, motion between the Pacific and North American plates along the Baja peninsula gradually changed from obliquely convergent slip along faults west of Baja California to strike-slip motion along the modern-day plate boundary in the Gulf of California [*Stock and Hodges*, 1989] (Figure 1). The transfer of the Baja peninsula to the Pacific plate during the eastward shift of the plate boundary is generally assumed to have been completed by 3.6 Ma, when seafloor spreading commenced along the Gulf rise in the southern Gulf of California. As a result, Gulf rise spreading rates have been used to derive several-million-year-average estimates of PA-NA motion in global plate motion models such as NUVEL-1 and NUVEL-1A [*DeMets et al.*, 1990; *DeMets et al.*, 1994].

If the Baja peninsula has been rigidly coupled to the Pacific plate since 3.6 Ma, then Gulf rise spreading rates should agree with independent estimates of PA-NA motion over comparable time intervals. Such estimates can be derived by requiring closure of global plate circuits that incorporate the Pacific and North American plates, but exclude all direct observations from the PA-NA boundary [e.g. *DeMets et al.*, 1990]; however, care must be exercised in interpreting discrepancies between the locally-estimated and closure-fitting rates because errors in the latter can arise from numerous sources within the interconnected global plate circuit. Here, seafloor spreading rates across the Gulf rise are compared to closure-fitting PA-NA rates to examine two questions - has Baja California been rigidly coupled to the Pacific plate since 3.6 Ma, and has motion between the Pacific and North American plates remained constant over the same interval?

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The Seafloor Spreading History of the Gulf Rise

To solve for the Gulf rise spreading history, all publicly available, ship-board magnetic data from cruises in the region of the Gulf rise were examined (Figure 2). Magnetic anomalies produced at the rise are crossed by eleven cruises, many of which have been analyzed in previous studies (e.g. *Larson* [1972], *DeMets et al.* [1987], *Lonsdale* [1995]). Residual magnetic intensities from these cruises were displayed in map and profile form, and were correlated with a synthetic magnetic profile (Figure 2). Tracks with obvious systematic navigational errors were eliminated from further consideration, and no attempt was made to correlate anomalies located over or near a prominent seamount northwest of the rise (Figure 2). Chrons 2An.1 and 2An.3 northwest of the rise were more difficult to correlate than the other anomalies due to their low amplitudes and irregular sampling.

Ship-track crossings of the old edge of chrons 1n and 2An.3, the young edge of chron 2An.1, and the middle of chrons 1r.1n and 2n were selected using an interactive data display, for a total of 54 anomaly crossings. Standard errors of 2.2 km, 1.6 km, and 1.0 km were adopted for anomaly crossings from cruises with pre-satellite, occasional satellite, and continuous satellite navigation, as suggested by analysis of numerous crossings of nearby Pacific-Rivera seafloor spreading lineations [S. Traylen and C. DeMets, unpublished data, 1995]. Astronomically-calibrated magnetic anomaly ages are taken from *Cande and Kent* [1995] (Table 1).

Time-averaged spreading rates for each of the five reversals modeled here are computed as follows: Best-fitting finite rotation angles are determined by fixing two of the three components of the finite rotation (latitude and longitude) to the NUVEL-1 PA-NA rotation pole and seeking the opening angle that minimizes the summed least-squares scatter of fixed and rotated anomaly crossings about a best-fitting great circle segment [*Hellinger*, 1981]. Best-fitting opening angles are then divided by their corresponding reversal age and the resulting angular velocity is used to predict a linear velocity for a point along the plate boundary. The spreading rate depends little on the assumed pole location provided that the pole predicts an opening direction close to ridge-normal, as does NUVEL-1. Confidence limits for the opening angles and thus spreading rates are determined by perturbing the best-fitting angle until the least-squares misfit increases more than expected for varying one parameter.

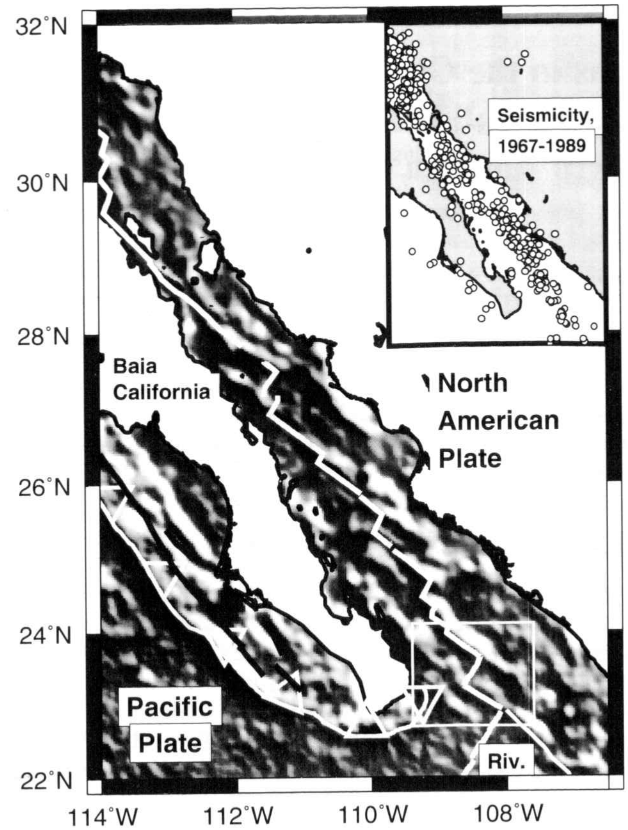

Figure 1. Kinematic setting, seismicity, and two minute marine gravity field of the Gulf of California. The modern-day PA-NA plate boundary is located in the axis of the Gulf. Seismicity west of Baja may represent continued slip along assorted offshore faults (black lines) located east of the inactive Cedros and San Lucas trenches. Inset in the southern Gulf outlines the region shown in Figure 2. Gravity is illuminated from the southwest and was provided courtesy of D. Sandwell (pers. commun., 1995). Faults are digitized from *Francheteau et al.*, [1983] and *Lonsdale* [1995].

The finite-average spreading rates derived from the 54 data show a significant 10-15% increase since 3.58 Ma (Table 1 and Figure 3). The least-squares misfit χ^2 is 19.2 for the 54 anomaly crossings, with a total of 39 degrees of freedom. Reduced chi-square is thus 0.5, indicating that the uncertainties given in Table 1 probably overestimate the true uncertainties by ~40% (although all uncertainties are admittedly based on small samples). One source of systematic error ignored here is outward displacement of magnetic anomalies that results from emplacement of newly extruded seafloor within and onto pre-existing seafloor [*Atwater and Mudie*, 1973]. Outward displacement inferred from Deep-Tow measurements along the nearby Pacific-Rivera rise is ~500 meters per reversal boundary [*Macdonald et al.*, 1980], implying that total opening distances are all overestimated by 1 km. Spreading rates corrected for this effect (Table 1) change too little to affect the conclusions drawn below.

To test whether the spreading acceleration shown in Figure 3 is statistically significant, the fits of two models are compared. One requires that the angular rotation rate has been constant since chron 2An.3; the other uses a different angular rotation rate for each of the five times modeled here. An iterative search for the best-fitting constant angular rotation rate gives $\dot{\omega} = 0.729°/\mathrm{Myr}$, with $\chi^2 = 57.5$. In contrast, χ^2 for the model with five adjustable rotation rates is 19.2. The improvement in the fit upon adding four adjustable parameters is significant at 1 part in 10^7. A constant spreading rate model can thus be rejected.

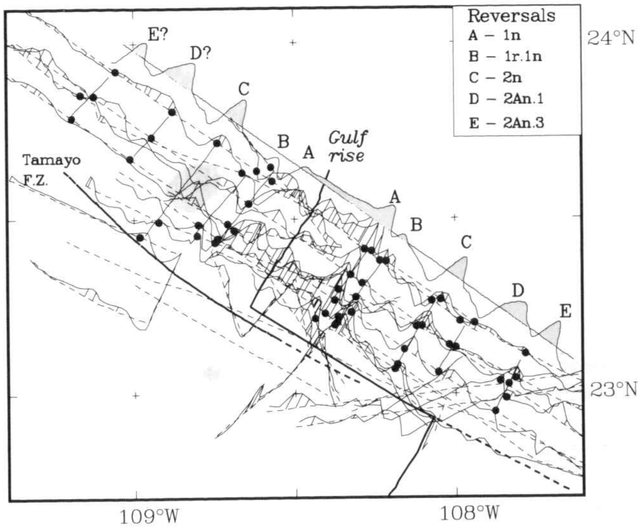

Figure 2. Along-track magnetic anomalies that record Gulf rise seafloor spreading. Anomaly crossings are shown as solid circles. The uppermost profile (with shaded positive anomalies) is a synthetic anomaly profile computed assuming a 49 mm yr^{-1} full spreading rate, and a phase shift appropriate for the Gulf rise spreading center. The Alarcon seamount, whose magnetization masks the nearby seafloor spreading lineations, is shown as a stippled region northwest of the Gulf rise.

To describe exactly how spreading has changed since 3.6 Ma, stage interval spreading rates were derived by differencing finite rotations for adjacent times. Spreading rates for the intervals 3.58-2.58 Ma, 2.58-1.86 Ma, and 1.86-0.78 Ma were 44.8±4.2, 40.3±5.8, and 44.2±3.2 mm yr^{-1}, but increased to 51.1±2.5 mm yr^{-1} thereafter. Thus, in the past 3.58 Myr, Gulf rise spreading rates appear to have changed significantly only once, at 0.78 Myr.

How fast is Pacific-North America Motion?

The above results demonstrate that post-3.6 Ma divergence rates between Baja California and the North American plate have increased 10-15%. If Baja California has been rigidly

Table 1. Gulf Rise Spreading Parameters

Chron	Age (Myr)	N	Opening Angle	Spreading Rate	Adjusted Rate†
1n	0.78	14	0.629°±0.033°	51.1±2.5	49.8
1r.1n	1.03	12	0.817°±0.036°	50.2±2.2	49.2
2n	1.86	10	1.384°±0.054°	47.1±1.5	46.6
2An.1	2.58	8	1.842°±0.049°	45.2±1.2	44.8
2An.3	3.58	10	2.549°±0.044°	45.1±0.8	44.8

All rates average to the present, are in units of mm yr^{-1}, and are computed at 23.5°N, 108.5°W. The rotation pole is fixed to the NUVEL-1 location of 48.7°N, 78.2°W. All uncertainties are 95%. *N* is the number of anomaly crossings inverted to find the rotation angle.

† Adjusted for outward displacement (see text).

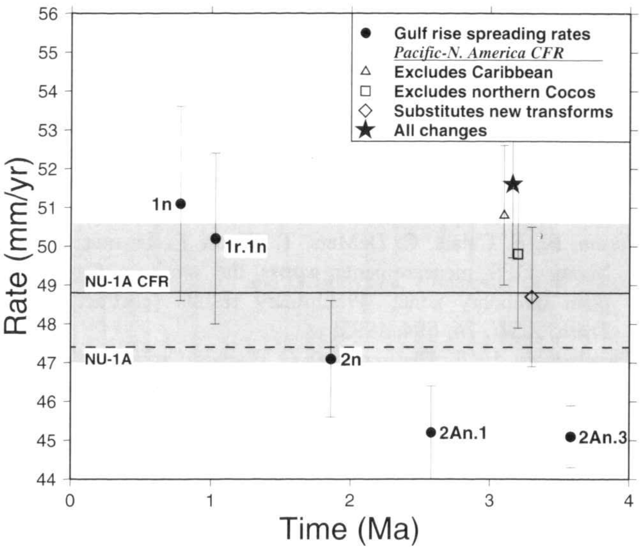

Figure 3. Time-averaged seafloor spreading rates for the Gulf rise (solid circles) and 3.16-Myr-average PA-NA motion closure-fitting rates (CFR) discussed in the text. Symbols representing the latter are staggered for clarity. All uncertainties, including the stippled region, are 95%.

coupled to the Pacific plate over the same interval, this implies that PA-NA motion has also increased and is now 4±2 mm yr^{-1} faster than the rate predicted by the widely used NUVEL-1A model (Figure 3). Because of the obvious importance of a recent acceleration in PA-NA motion to the many geologic and geodetic research efforts focused on the western United States, it thus seems prudent to examine whether Baja California has indeed been part of the rigid Pacific plate since 3.6 Ma.

This can be accomplished by comparing Gulf rise spreading rates to 3.16-Myr-average PA-NA "closure-fitting rates", which are derived from globally-distributed kinematic observations that exclude spreading rates from the Gulf of California. The PA-NA closure-fitting rate predicted from the NUVEL-1A kinematic data is 48.8±1.8 mm yr^{-1} (hereafter, all errors are 95% and have been adjusted such that reduced chi-square is 1.0 for the relevant model), indicating that data from other plate boundaries are fit better if the PA-NA rate is higher than the Baja-North America rate derived from Gulf rise spreading rates.

To investigate the possibility that this discrepancy is merely an artifact of possible systematic errors in the NUVEL-1(A) kinematic data, several modifications to these data, each designed to remove a likely source of error in estimates of Pacific-North America velocities, are investigated below. The emphasis is on whether these changes reduce the observed difference between the Gulf rise spreading rate and the PA-NA closure-fitting rate, as might be expected if this difference arises solely from random or small systematic errors in globally-distributed kinematic data.

Elimination of Circum-Caribbean Kinematic Data

Circum-Caribbean kinematic data and plate circuit closures are arguably the most problematic aspect of the NUVEL-1 data and model. Fitting the circum-Caribbean kinematic data while satisfying global plate circuit closures results in a significant misfit to earthquake slip vectors from the Lesser Antilles trench, as well as a predicted Caribbean-North America spreading rate of only 12±6 mm/yr [*DeMets et al.*, 1990]. This is significantly slower than a 23±4 mm yr^{-1} rate estimated from GPS measurements of 1986-1994 displacements between sites spanning the Caribbean-North America plate boundary at the longitude of Hispaniola [*Farina et al.*, 1995]. These discrepancies suggest that some subset of the 78 NUVEL-1 circum-Caribbean kinematic data is biased by unmodeled deformation along the edges of or within the Caribbean plate (e.g. *Heubeck and Mann* [1991]). To eliminate any adverse effect of these data on estimates of global plate velocities, all 78 circum-Caribbean data are excluded.

Substitution of Southern Hemisphere Transform Azimuths

Prior to the advent of dense altimetric measurements of the marine gravity field, only 56 of the more than 100 transform faults south of 30°S were mapped well enough to be useful for estimating plate slip directions. As a result, spreading centers south of 30°S provided less than 20% of the kinematic information in NUVEL-1, even though they comprise ~40% of the mid-ocean ridge system. *Spitzak and DeMets* [1995] demonstrate that 108 transform fault azimuths derived from dense altimetric observations south of 30°S are consistent with their bathymetrically-derived counterparts, including azimuths determined from multi-beam and side-scan sonar surveys. Here, the new catalog of transform fault azimuths derived by Spitzak and DeMets, including those derived from multi-beam and side-scan sonar surveys, are substituted for those used to derive NUVEL-1(A).

Elimination of Northern Pacific-Cocos Spreading Rates

A recent, detailed analysis of anomaly crossings from the Pacific-Cocos-Nazca plate circuit demonstrates that numerous anomaly crossings from the East Pacific rise north of ~13°N are misfit by best-fitting and closure-enforced Pacific-Cocos rotations [D. Wilson, "Relative motion of the Cocos, Nazca, and Pacific plates for anomalies 1-3", in prep., 1995]. This result corroborates a previously-noted misfit to 3.16-Myr-average Pacific-Cocos spreading rates from the northernmost East Pacific rise [*DeMets et al.*, 1990]. It is unclear whether the observed misfit results from continued slow spreading along the Mathematician rise after its supposed extinction at 3.58 Myr or possibly from internal deformation of the Cocos plate; however, spreading along the northern Pacific-Cocos rise does not appear to record Pacific-Cocos motion. Consequently, the eight NUVEL-1(A) spreading rates from this region are omitted.

Effects on the Pacific-North America Closure-Fitting Rate

To determine the individual and cumulative effects of the changes described above on the closure-fitting PA-NA rate, the 1117 NUVEL-1A data (excluding the five Gulf rise spreading rates) are used to construct four global plate motion data sets, three of which incorporate the individual changes proposed above and one of which incorporates all three changes. Inversion of the first three data sets yields closure-fitting rates that are higher than Gulf rise spreading rates (Figure 3); the data set that incorporates all three changes yields a closure-fitting rate of 51.6±1.9 mm yr^{-1}. The discrepancy between the 3.16-Myr-average Gulf rise spreading rate and the PA-NA closure-fitting rate thus remains the same or increases in response to these plausible changes in the NUVEL-1(A) data.

Discussion

The results presented above can be interpreted in either of two ways. The similarity between the 3.16-Myr-average closure-fitting PA-NA rates and 0.78 Myr- and 1.03 Myr-average Gulf rise spreading rates might indicate that PA-NA motion has remained constant since ~3 Ma. In this case, the observation that Baja peninsula-North America spreading rates prior to 0.78 Ma were significantly slower than the full PA-NA rate implies that some PA-NA motion was accommodated on structures other than the Gulf rise up until 0.78 Ma.

The fraction of PA-NA motion not recorded along the Gulf rise could have been accommodated in at least two ways. The Baja peninsula could have moved relative to the Pacific plate up until ~1 Ma, after which any remaining motion along faults west of Baja California shifted eastward to the present plate boundary. Continued seismicity along faults west of the Baja peninsula (Figure 1) and seismic reflection profiles suggestive of recent movement along these faults [*Spencer and Normark, 1979*; *Normark et al.*, 1987] suggest that the southern Baja peninsula may still move slowly relative to the Pacific plate. Alternatively, the change from distributed extension in the southern Gulf prior to ~3.6 Ma to seafloor spreading along the Gulf rise may have involved a period during which divergence was partitioned between the wider, pre-existing zone of extension and the newly-active Gulf rise.

In the less likely event that Gulf rise spreading rates have recorded the full PA-NA rate since 3.6 Ma, the Gulf rise stage spreading rates demonstrate that PA-NA motion has increased by 10-15% since ~1 Ma. The persistent discrepancy between the closure-fitting and observed Gulf rise rates must then be attributed to an error in data or an unmodeled plate boundary elsewhere within the global circuit. This seems unlikely due to the demonstrated low level of plate circuit non-closure in NUVEL-1(A) [*DeMets et al.*, 1990], and the persistence of the observed discrepancy upon modifications to the global kinematic data.

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