# A Kinematic Model of Ridge-Transform Geometry Evolution

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**Abstract.** Spreading ridge-transform geometries will remain stable so long as accretion is symmetric. Asymmetric accretion, however, will cause lengthening or shortening of transforms and, in extreme cases, may result in zero-offset transforms (ZOTs) and very-long-offset transforms (VLOTs) such as the Ninetyeast and Chagos transforms. We use a simple kinematic model to examine the effects of various parameters on the evolution of zero-offset transforms and very-long-offset transforms. Starting with the transform length spectrum found along the Mid-Atlantic Ridge distributed in a randomly determined ridge-transform configuration, we allow for asymmetric accretion along ridge segments, assuming that individual ridge segments act independently. We analyze the effects of initial configuration, degree of asymmetry, and degree of bias in asymmetry on the generation of very-long-offset and zero-offset transforms. Finally, we examine the effect of these parameters on the possible steady-state nature of the transform length spectra. This model predicts that zero-offset transforms can be generated with a minimum of asymmetry, and that bias in asymmetry and initial ridge-transform-ridge configuration have no effect on generation of ZOTs. Similarly, random variations in spreading asymmetry have difficulty generating significant increases in transform length, so VLOTs may be manifestations of dynamic processes. Of the parameters tested, only lack of 'memory' of zero-offset transforms has any effect on transform length distribution, and therefore, the transform length spectrum remains steady-state if ZOTs have some degree of memory.

## 1. Introduction

As increasingly detailed bathymetric and magnetic data become available, our view of the ridge-transform-ridge system of spreading centers becomes more and more complex (Fox and Gallo, 1984). The simplest possible geometry for an oceanic spreading center, symmetric and orthogonally spreading ridge segments offset by transform faults (Wilson, 1965), will not change as a function of time, since the length of the transform faults remains constant. Comparison of present and past ridge geometries, however, shows that the geometry of oceanic ridge-transform systems can change significantly with time. The most dramatic cases are ones in which entire spreading centers became extinct and were replaced by new ones, as has occurred along various sections of the East Pacific Rise (Menard *et al.*, 1964; Herron, 1972; Mammerickx *et al.*, 1980).

Even in cases like the Mid-Atlantic Ridge, where no major segments have been abandoned, such that the overall geometry has remained relatively constant, individual segments have undergone changes in geometry. Figure 1 (Brozena, 1986) shows magnetic anomalies along a portion of the southern Mid-Atlantic Ridge. The changes in the distance between corresponding pairs of anomalies on either side of transform offsets demonstrate that the length of transforms has varied with time. In some cases the lengths increased, and in others they decreased. In the latter situation, the transform offset sometimes seems to have shrunk to essentially zero (on the scale observable with these data) and then increased again. Transform A′, for example shrinks to zero offset between anomaly 5b and 4 times (15 Ma and 7 Ma, respectively), remains at zero offset until anomaly 3′ (6 Ma), at which time it develops a small left-lateral offset. It then shrinks to zero again at anomaly 2 time (2 Ma), finally developing into a right-lateral offset at present. Such cases, in which transforms of initially discernible offset have shrunk to zero offset, are discussed by Schouten and White (1980). The reverse process, in which transforms grow to very long offsets, has been proposed for the Chagos (Fisher *et al.*, 1971) and Ninetyeast (Sclater and Fisher, 1974) Transforms in the Indian Ocean. We refer to such long transforms, which have increased their length significantly, as 'VLOTs'.

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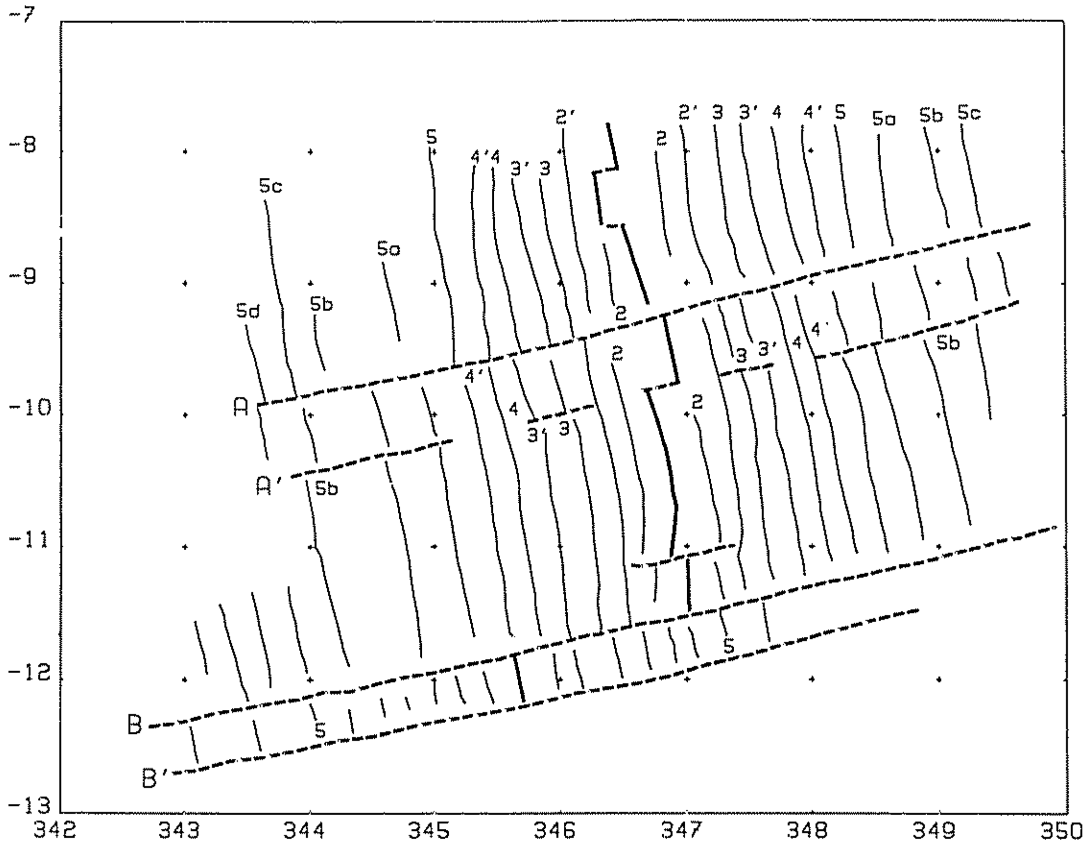


Fig. 1. The southern Mid-Atlantic Ridge (heavy line) and magnetic anomalies. Transform A′ reaches zero offset at anomaly 4 and 4′ time, and again at anomaly 2 and 2′ time. Offset along A′ is 15 km at anomaly 5b, 10 km at anomaly 3, and 20 km at present. 35% asymmetry in spreading is required to reach zero-offset (after Brozena, 1986).

For such transform length changes to have occurred, lithosphere *must* have been accreted asymmetrically about the ridge axis. In theory, this process could occur in several ways (Menard, 1984). Individual ridge segments can spread asymmetrically (Dickson *et al.*, 1968; Weissel and Hayes, 1971, 1974; Johnson *et al.*, 1972; Macdonald, 1977; Macdonald and Luyendyk, 1977; Stein *et al.*, 1977) such that material is preferentially accreted at the ridge axis itself (Sleep and Rosendahl, 1979). Alternatively, lithosphere can be formed on one plate and transferred to another by several possible mechanisms including rift propagation (Hey, 1977; Hey *et al.*, 1980; Hey and Wilson, 1982; Johnson *et al.*, 1983; Wilson *et al.*, 1984; Searle and Hey, 1983; Hey *et al.*, 1986; Miller and Hey, 1986; Acton *et al.*, 1987), microplate formation (Menard, 1978; Mammerickx *et al.*, 1980; Rea and Dixon, 1983; Engeln and Stein, 1984; Tamaki and Larson, 1987; Engeln *et al.*, 1987), or discrete ridge jumps (Shih and Molnar, 1975; Winterer, 1976). The different modes of asymmetric accretion can be discriminated, when the dimensions of the area being transferred is large enough. In a case like that shown in Figure 1, however, it is difficult to do so.

In this paper we use simple numerical models of ridge-transform geometries to explore the question of whether zero-offset and very long offset (i.e. ones which have undergone large length changes) transforms can be regarded as having been formed purely by the random perturbations in the spreading process. If this is not the case, zero-offset and very long offset transforms may result from a dynamical process different from those normally operating. We begin with the observed present day transform length spectrum, since the distribution of transform and ridge crest lengths has recently been compiled (Abbott, 1986; Sandwell, 1986), and simulate the changes expected with time. In addition to simulating the formation of zero-offset and very long offset transforms, these experiments lead naturally to the question of whether the observed present day spectrum is a steady state one. This is suggested by the observation that the present Mid-Atlantic Ridge retains the shape of the continental breakup from the opening of the Atlantic.

## 2. The Model

Figure 2 shows the model we are exploring. We assume that individual ridge segments spread independently with a fixed full spreading rate (30 mm yr$^{-1}$), and treat the half-rates on each segment as a random function of three variables. The first two are parameters for a Gaussian distribution of half spreading rates: the standard deviation ($\sigma$ in Figure 2) representing the fraction or degree of asymmetry, and the mean ($\mu$) representing a possible bias in the sense of asymmetry. The bias parameter represents the possibility that over extended ridge lengths different segments may show a strong preferred sense of asymmetry, as often observed (Stein *et al.*, 1977; Vogt *et al.*, 1982). The third parameter measures the memory, the probability of renewed motion, for transforms in a zero-offset state. Large values (50–100%) correspond to Schouten and White (1980) and Schouten and Klitgord's (1982) proposal that zero-offset transforms (ZOT) will later be reactivated. Small memory values correspond to the alternative (K. Macdonald, pers. comm.) that any transform which goes to zero-offset will not be reactivated, but may remain as one of the complex local features on the ridge, such as an overlapping spreading center or other type of small non-overlapping offset (Batiza and Margolis, 1986; Langmuir *et al.*, 1986). For our modeling purposes, a ZOT is simply a very small offset relative to the scales used; and given the minor deviations from axial linearity that appear to persist, (Schouten and White, 1980) this modeling limitation is not a serious one. Throughout this model, it is assumed that there is no nucleation of new offsets; that is, the only possible locations of transforms are the original transform sites. Examples of the effects of these parameters are shown in Figure 3.

Starting with a sample initial configuration (Figure 3a), the results of three models are given in Figures 3b–3d. Strong asymmetry in spreading leads to relatively large variations in transform lengths (compare transforms 'C' and 'D' in b and d with 'C' and 'D' in c). In Figure 3d the right-hand side of the ridge obviously spreads consistently slower than the left-hand side, reflecting a high degree of bias. The effect of memory can be seen by comparing b with c and d: for the no-memory case (b), once transforms go to zero-offset, they remain at zero-offset throughout the model (transforms 'A' and 'C' in b), while for total memory cases transforms that go to zero-offset do not tend to remain at zero-offset ('A', 'C', and 'D' in d).

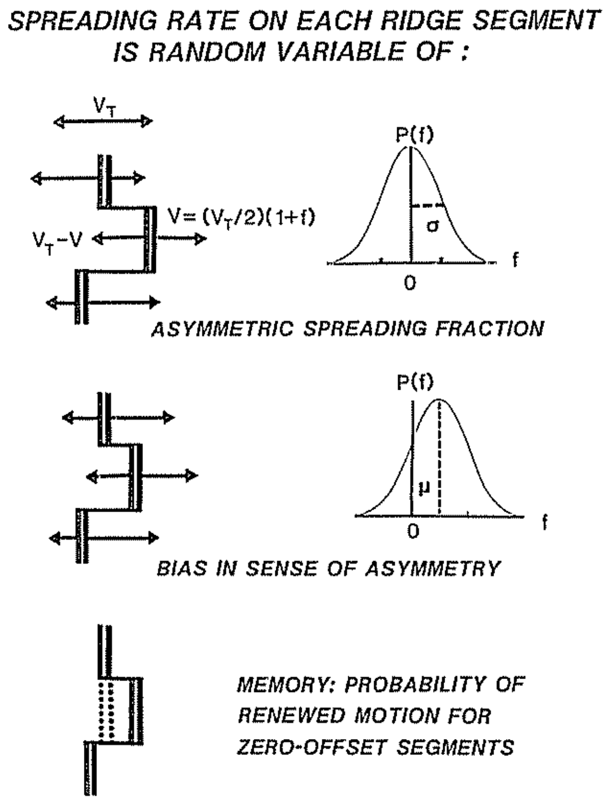


Fig. 2. Parameters for simple ridge-transform evolution model. $V_T$ is the total (full) spreading rate, taken as constant along the spreading ridge. $V$ is the velocity of the right-hand side, determined from the asymmetric spreading fraction, $f$, as shown $f$, in turn, is determined from $P(f)$, a Gaussian distribution centered about $\mu$, with standard deviation, $\sigma$.
*Top:* The size of the asymmetric spreading fraction (and therefore, the degree of asymmetry) is controlled by the standard deviation ($\sigma$) of the Gaussian distribution of fractional asymmetry in half spreading rates $\sigma$ varies from 0.05 to 0.25.
*Center:* Asymmetry bias: mean ($\mu$) of Gaussian distribution, representing possible preferred sense of asymmetry. Moderate bias ($\mu = 0.1$) case is shown. Models were run for $\mu = 0.0$ (no bias), $\mu = 0.1$, and $\mu = 0.2$ (strong bias).
*Bottom:* Memory, the probability of renewed motion, for transforms once in a zero-offset state. Large memories favor renewed motion small values correspond to zero-offset transforms not reactivating.

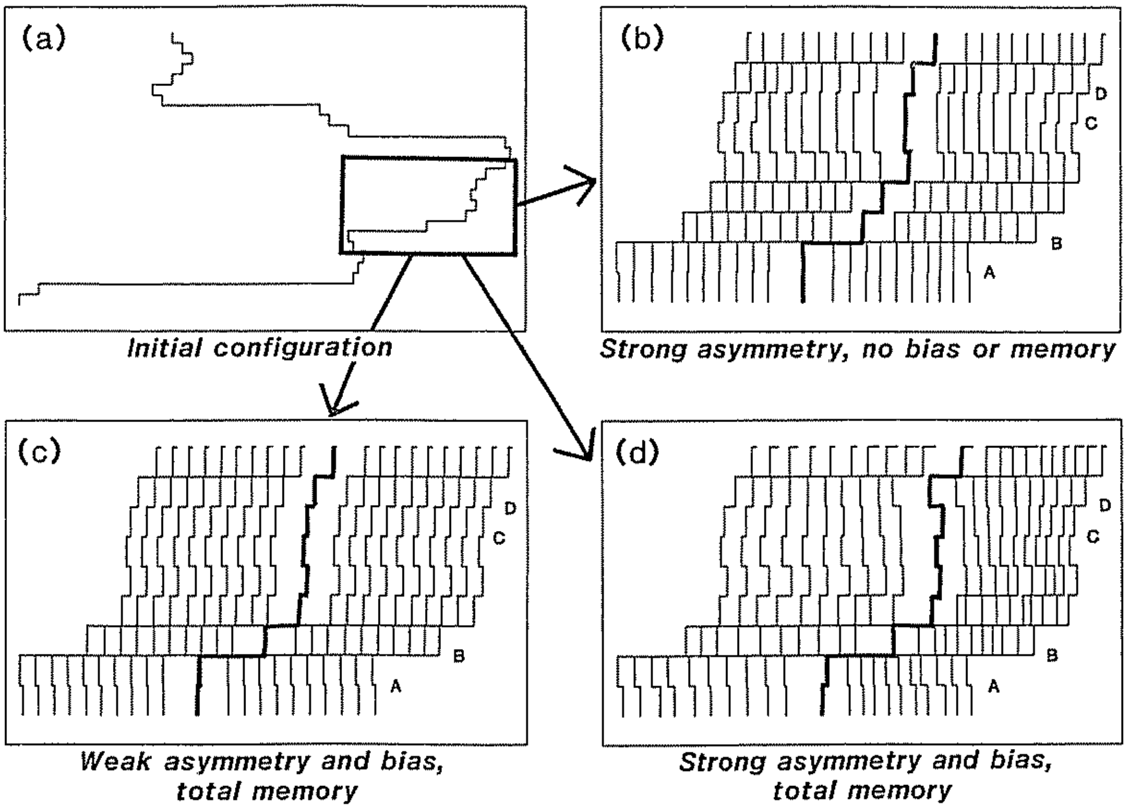


Fig. 3. Portion of three of the final configurations corresponding to boxed region of an initial configuration (a), after 25 one-million year time steps and using an average half-rate of 15 mm yr$^{-1}$. Note effects of different values of the three parameters. (b) No memory: preserves largest number of zero-offset transforms (ZOTs remain at zero-offset such as transforms 'A' and 'C'). (c) Weak ($\sigma = 0.05$) asymmetry and bias ($\mu = 0.0$): Anomaly pattern is symmetric about ridge, transforms remain at relatively constant length. (d) Strong ($\sigma = 0.25$) asymmetry and bias ($\mu = 0.2$): Anomalies are wider west of ridge, transform lengths vary greatly. ZOTs form easily, but do not persist (transforms 'A', 'C', and 'D', for example).

In this study, two different groups of experiments were run: the first to test for generation of zero-offset transforms, and the second to test for generation of very-long-offset transforms. The ZOT experiments were run for four degrees of asymmetry ($\sigma = 0.05$, 0.10, 0.15, and 0.20), three degrees of bias in asymmetry (none, moderate, and very strong, corresponding to $\mu = 0.0$, 0.1, and 0.2), and three degrees of memory (0, 50, 100%). Additionally, ten different initial ridge-transform configurations (lettered a–j) were used. Each configuration consists of 26 ridge segments and the 25 transforms connecting them. Each was randomly generated such that the transform length distribution was the same as that of the Mid-Atlantic Ridge, as determined by Abbott (1986). Six had random sense of offset, while four had uniform sense of offset (either all right-lateral or all left-lateral). A total of 324 trials were run, each with 25 one million year time steps. For the VLOT experiments the effects of asymmetry, bias, and memory were tested using five of the initial configurations used in the ZOT experiments. The effects of asymmetry (up to 25%) and bias (for the extremes of $\mu = 0.0$ and 0.2) were further tested using all ten initial configurations.

Such a model attempts to describe the kinematics of the system in an average, overall sense rather than the dynamics of an individual spreading cell. Despite its simplicity, it is a natural way to approach the complexity of the spreading system, so long as segments can be regarded as acting independently. Such an approach has been used by Schouten and Klitgord (1982); a conceptually similar model in which spreading rates are used as independent random variables is used by Batiza and Margolis (1986). Such models should be useful for a wide range of possible dynamic behavior of the ridge axis; they only require that at some scale the spreading behavior of segments be independent of adjacent ones, so that their time histories can differ, with some segments spreading more rapidly with time than others. This is a natural consequence of models in which spreading occurs by local magmatic pulses, as suggested by studies of overlapping spreading centers (Sempere and Macdonald, 1986), small non-overlapping offsets (SNOOs) of the ridge axis (Batiza and Margolis, 1986), and rapid along-axis petrological variations (Langmuir *et al.*, 1986). In our model we used the approximation that the average full spreading rate over a time was constant; however, this could, of course, also be varied within limits. Although in ours, or any numerical simulation, the results are predictions of a particular model, we feel that they offer some useful insights that are hard to derive otherwise. This approach is in some ways conceptually similar to the numerical models used to simulate faulting processes (Dieterich, 1974).

## 3. Results

### 3.1. ZERO-OFFSET TRANSFORMS

The results of the ZOT experiments are summarized in Figure 4. For each parameter, the number of ZOTs (given as a percentage of the total number of transforms) is plotted as a function of time. The number of zero-offsets generated by each of the 324 runs was calculated at each of the 25 time steps, and then added together to get a total number of ZOTs per time step as a function of time. This number was then broken down as a function of starting assumption for each of the four kinematic factors being tested.

As expected, the initial configuration had no significant effect (Figure 4a). The uniform offset configurations (heavy lines) are not found to bunch together, but rather are found at the high, low, and intermediate regions of the plot. No individual configuration differs significantly from average.

The presence or absence of bias (Figure 4c) had no effect on the number of zero-offsets produced. Although at first glance surprising, this is to be expected. In a ridge-transform-ridge system, if both ridge segments experience the same bias, i.e. both spread faster towards the west, the configuration, and hence transform length, remains the same. If the sense of bias differs, however, such that one segment spreads faster to the east while the other spread faster to the west, then the length of the transform will change with time.

Also as expected, the fraction of zero-offsets produced increased with the degree of asymmetry (Figure 4b) and decreased with amount of memory (Figure 4d). Of interest is that ZOTs are generated even for the smallest asymmetry (5%). Also, the number of ZOTs seems to reach steady-state for the 50% and 100% memory cases relatively soon in the model. It is expected that for the 0% memory case the percent of ZOTs will approach 100% with time.

### 3.2. VERY-LONG OFFSET TRANSFORMS

The results of the VLOT experiments are summarized in Figure 5. Figure 5a shows percentage of transforms as a function of percent growth for transforms initially 4 km (short dashes) to 256 km (long dashes) long. Only the short transforms experienced any significant growth, reaching up to four times their initial length. While the longer transforms may have had similar absolute growth ($\sim$20 km), their percent growth rarely reached 100%. As in the case of the zero-offset transforms, variations in bias and initial configuration had no effect on the range of growth of transforms (Figures 5b and 5c, shown for initial length of 4 km). While transform memory affects the length distribution, it has no apparent effect on maximum growth of transforms (Figure 5d). The tall spike for the zero memory case is a result of the large number of zero-offsets generated by this model. The only factor tested that affected the maximum growth was the degree of asymmetry (Figure 5e). The curve for 20% asymmetry (long dashes) reflects both the increase in maximum growth, and the generation of more zero-offsets. The 5% curve appears to approximate a Gaussian distribution about 0% growth.

The numerical model suggests that it is difficult to obtain substantial growth of initially long transforms for any combination of kinematic factors. If our model is at all appropriate, the development of long transforms into Ninetyeast- or Chagos-style transforms may require a dynamical origin beyond the random fluctuation of the spreading process. Peirce (1978), for example, suggests that large ridge jumps were associated with the evolution of the Ninetyeast transform. Alternatively, a major change in plate geometry, such as subdivision or suturing of plates, for example, may result in a major transform length change. This has been proposed for the Ninetyeast, Chagos, and Romanche transforms (D. Abbott, pers. comm.).

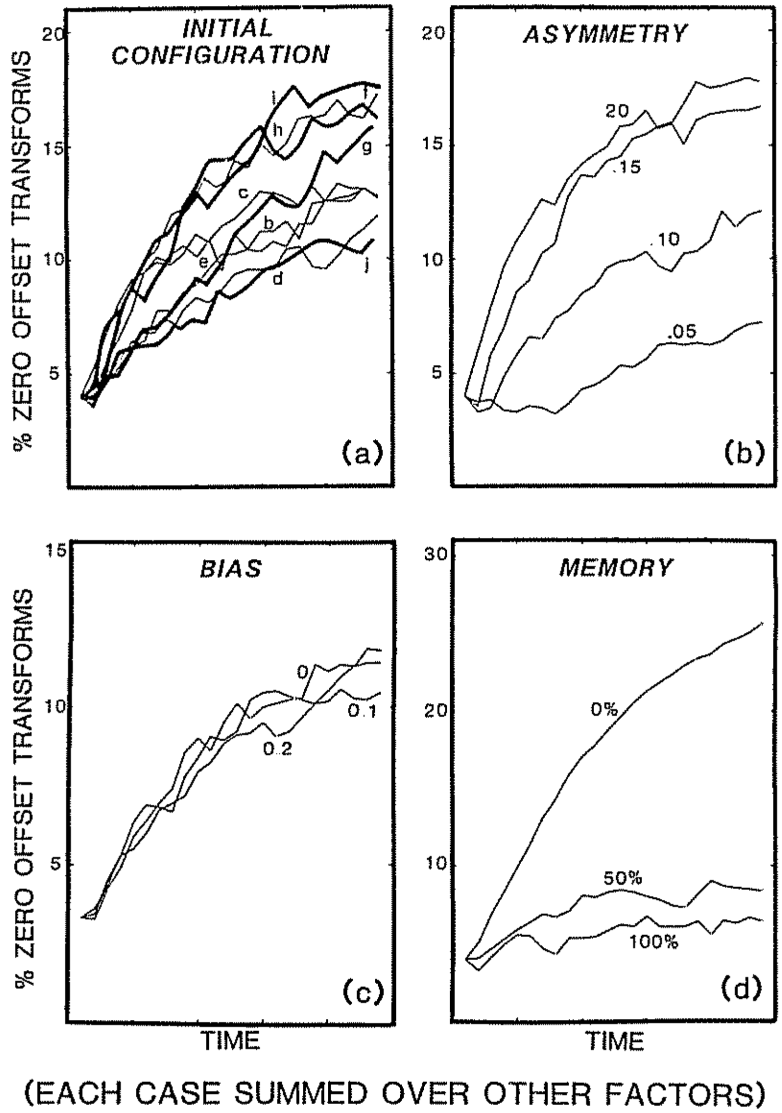


Fig. 4. Percentage of zero-offset transforms as a function of time for different factors. The graphs show total number of ZOTs at each time step. The general increase in number of ZOTs with time is due to the zero memory case (a) Initial configuration (Models a–j). Uniform-offset initial configurations (heavy lines, models a–f) behave no differently than random offset configurations (models g–j). (b) Asymmetry. As expected, the largest number of ZOTs is generated by the strongest asymmetry case ($\sigma = 0.20$). Note, however, that even the weakest case ($=0.05$) produces ZOTs. (c) Bias. The three different cases (none, moderate, and strong; represented by $\mu = 0$, 0.1, and 0.2 curves, respectively) have no effect on generation of ZOTs. (d) Memory. The no memory (0%) case should asymptotically approach 100% ZOTs as time increases. The partial (50%) and total (100%) cases apparently reach a steady-state percentage of ZOTs.

### 3.3. Transform Length Spectrum

The predictions of the model can be summarized by examining the change in transform length spectrum between initial and final configuration as a function of kinematic factors. Figure 6 shows the basic result; the observed Atlantic transform length spectrum does not change significantly except for the case when transform memory is small. The three spectra for the different bias cases are all virtually identical to the initial distribution (Figure 6a). The small departures produced in the asymmetry experiments (Figure 6b) reflect a combination of high asymmetry and no memory, as only the zero-memory case (Figure 6c) results in a change in length spectrum. In other words, unless transforms which evolve to zero-offset tend to remain so, the observed Atlantic transform spectrum is steady state. In the absence of a mechanism preferentially driving transforms to longer offsets, or keeping them at zero (memory), the random variations

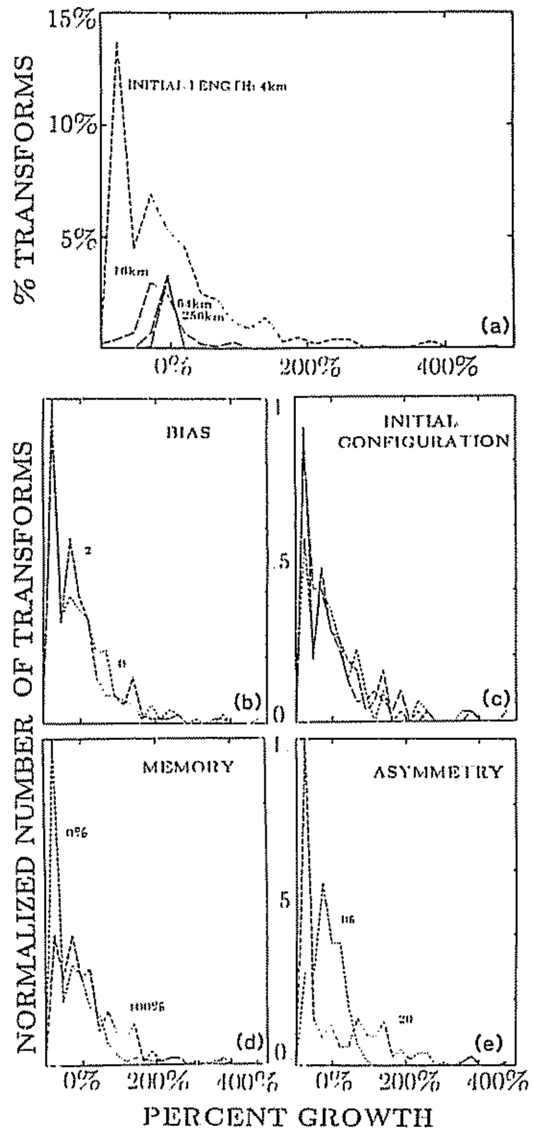


Fig. 5. Results of very-long-offset transform experiments. (a) Percentage growth in transform length as function of initial length. The process rarely resulted in significant (>400%) increases in transform length except for the very short transforms. (b–e) Percent growth in transform length as a function of time for different factors. (b) Bias. (c) Initial configuration. (d) Memory. (e) Asymmetry.

in transform length will not change the transform spectrum.

## 4. Discussion

Another look at Figure 3 shows that the ridge-transform geometry varies with time in a fashion similar to that observed along the Mid-Atlantic Ridge (Figure 1; Brozena, 1986). Although individual transforms change length, the overall configuration and transform length spectrum do not seem to change significantly. More specifically, while the shorter transforms (i.e. A′ in Figure 1, A in Figure 3) may go to zero-offset or even reverse their sense of offset, the length of the longer transforms does not change significantly (transform B in Figures 1 and 3, for example). Thus, the model parameters which predict a steady state transform length spectrum seem appropriate, although a detailed analysis of transform length spectra at past times would be needed to prove this. Since the steady state length spectrum requires some degree of transform memory, these simulations favor the idea that some process or combination of processes provide it. The model cannot, of course, indicate physically how this occurs: possibilities include the persistence of independent spreading systems even once the offset is quite small, or simply the combination of spatially limited magmatic pulses and the inherent weakness of the fracture zone associated with a ZOT.

We feel that the simple numerical model offers some useful insights. We thus regard it as an initial model, for which more sophisticated extensions may be justified. One possibility would be to examine the effect of other initial length spectra, using those for the other ocean basins, initially to see if they are also in steady state. Similarly, it would be interesting to see whether other initial spectra will evolve into spectra like those presently observed, and whether differences in the spectra, like those observed in different oceans, can result from the factors considered here. If not, perhaps spreading rate dependent parameters, such as different characteristic times for different kinematic factors, can result in differences between oceans.

An important further test involves transform memory. This model suggests that there must be at least some memory at zero-offset transforms. It does not allow, however, for generation of new transforms along ridge segments. Obviously, if new transforms are generated at the same rate as old ones go to zero-offset, the number of finite-offset transforms could remain constant, even with no transform memory. A second test would be to allow memory to decrease with time, so that if a transform happens to remain at zero-offset for any length of time, the chance of it lengthening again would decrease. This may be the case if each ridge segment has its own magma chamber. The longer the ridge segments remain aligned,

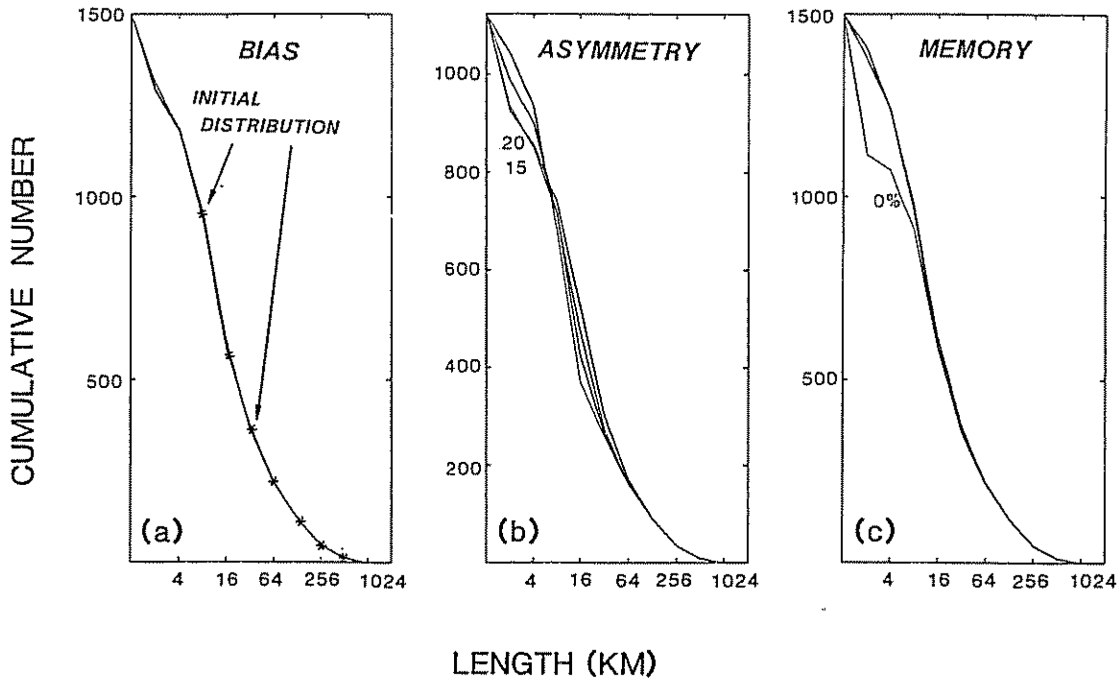


Fig. 6. Change in transform length distribution between initial and final configuration as a function of kinematic factors. The initial (observed Atlantic; Abbott, 1986) transform length spectrum does not change significantly except when transform memory is small. Thus, in this model, unless transforms which evolve to zero-offset tend to remain so, the observed Atlantic transform spectrum is steady state. (a) Bias. Asterisks show original spectrum from Abbott (1986), normalized to our model. (b) Asymmetry (c) Memory.

the more the two separate chambers may consolidate into one, thus effectively eliminating any trace of the transform.

A feature not included in the present model is that the variation in transform lengths will cause a variation in ridge segment lengths, as transforms go to zero-offset. It would be interesting to incorporate this effect in later models, since the available data show a clear spreading rate dependence of ridge crest lengths (Abbott, 1986) which has been interpreted as reflecting ridge dynamics (Schouten *et al.*, 1985). If this interpretation is correct, the numerical experiment would explore whether the spreading rate dependence of ridge segment length, though ultimately of dynamic origin, may be accomplished through the kinematics of the spreading process.

Another feature that might usefully be incorporated is the generation of spready obliquity by these processes. We regarded each segment as independent and allowed asymmetric but not oblique spreading. Since the along-axis spreading variations we treated could change the ridge axis trend from the normal to the spreading direction, oblique spreading and hence interesting changes in spreading geometry (Menard, 1984) might easily result.

## 5. Summary

The major prediction from this model is that relatively small changes in ridge-transform geometries are to be expected from minor random variations to normal symmetric spreading processes, but large changes require some alternative processes. Therefore, such features as zero-offset transforms and short transforms that change their sense of offset are not directly indicative of dynamic forces, although the ability of segments to spread independently ultimately reflects the spreading process. In contrast, the growth of very-long offset transforms, or any transforms that undergo large changes in length, should not be expected from random variations. A consequence of this prediction is that overall transform length distribution for a ridge system should remain essentially steady state in the absence of transform memory or effects tending to significantly increase transform length.

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## References


Abbott, D., 1986, A Statistical Correlation between Ridge Crest Offsets and Spreading Rate, *Geophys. Res. Letters* **13**, 157–160.

Acton, G. D., Stein, S., and Engeln, J. F., 1988, Formation of Curved Seafloor Fabric by Changes in Rift Propagation Velocity and Spreading Rate: Application to the 95.5° W Galapagos Propagator, *J. Geophys. Res.* **93**, 11845–11861.

Batiza, R. and Margolis, S. H., 1986, Small Non-Overlapping Offsets of the East Pacific Rise, *Nature* **320**, 439–441.

Brozena, J. M., 1986, Temporal and Spatial Variability of Seafloor Spreading Processes in the Northern South Atlantic, *J. Geophys. Res.* **91**, 497–510.

Dickson, G. L., Pitman, W. C. III, and Heiritzler, J. R., 1968, Magnetic Anomalies in the South Atlantic and Ocean Floor Spreading, *J. Geophys. Res.* **73**, 2087–2100

Dieterich, J. H., 1984, Earthquake Mechanisms and Modeling, *Ann. Rev. of Earth and Plan. Sciences* **2**, 275–301.

Engeln, J. F. and Stein, S., 1984, Tectonics of the Easter Plate, *Earth Planet. Sci. Letters* **68**, 259–270

Engeln, J. F., Stein, S., Werner, J., and Gordon, R., 1988, Microplate and Shear Zone Models for Oceanic Spreading Center Reorganization, *J. Geophys. Res.* **93**, 2839–2856.

Fisher, R. L., Sclater, J. G., and McKenzie, D. P., 1971, Evolution of the Central Indian Ridge, Western Indian Ocean, *Geol. Soc. Am. Bull.* **82**, 553–562.

Fox, P. J. and Gallo, D. G., 1984, A Tectonic Model for Ridge-Transform-Ridge Plate Boundaries: Implications for the Structure of Oceanic Lithosphere, *Technophysics* **104**, 205–242.

Herron, E. M., 1972, Sea-Floor Spreading and the Cenozoic History of the East-Central Pacific, *Geol. Soc. Am. Bull.* **83**, 1671–1691.

Hey, R., 1977, A New Class of 'pseudofaults' and their Bearing on Plate Tectonics: A Propagating Rift Model, *Earth Planet. Sci. Letters* 37, 321–325.

Hey, R. N. and Wilson, D. S., 1982, Propagating Rift Explanation for the Tectonic Evolution of the Northeast Pacific – the Pseudomovie, *Earth Planet. Sci. Letters* **58**, 167–188.

Hey, R., Duennebier, F. K., and Morgan, W. J., 1980, Propagating Rifts on Mid-Ocean Ridges, *J. Geophys. Res.* **85**, 3647–3658.

Hey, R. N., Kleinrock, M. C., Miller, S. P., Atwater, T. M., and Searle, R. C., 1986, Sea Beam/Deep-Tow Investigation of an Active Oceanic Propagating Rift System, Galapagos 95.5° W, *J. Geophys. Res* **91**, 3369–3393.

Johnson, G. L., Southall, J. R., Young, P. W., and Vogt, P. R., 1972, Origin and Structure of the Iceland Plateau and Kolbeinsey Ridge, *J. Geophys. Res* 77, 5688–5696.

Johnson, H. P., Karsten, J. L., Delaney, J. R., Davis, E. E., Currie, R. G., and Chase, R. L., 1983, A Detailed Study of the Cobb Offset of the Juan de Fuca Ridge: Evolution of a Propagating Rift, *J. Geophys. Res.* **88**, 2297–2315.

Langmuir, C. H., Bender, J. F., and Batiza, R., 1986, Petrologic and Tectonic Segmentation of the East Pacific Rise 5°30′–14°30′ N, *Nature* **322**, 422–429.

Macdonald, K. C., 1977, Near Bottom Magnetic Anomalies, Asymmetric Spreading, Oblique Spreading and Tectonics of the Mid-Atlantic Ridge near Lat 37° N, *Geol. Soc. Am. Bull.* **88** 541–555.

Macdonald, K. C. and Luyendyk, B. P., 1977, Deep-Tow Studies of the Structure of the Mid-Atlantic Ridge Crest near Lat 37° N, *Geol. Soc. Am. Bull* **88**, 621–636.

Mammerickx, J., Herron, E., and Dorman, L., 1980, Evidence for Two Fossil Spreading Ridges in the Southeast Pacific, *Geol. Soc. Am Bull.* **91**, 263–271.

Menard, H. W., 1978, Fragmentation of the Farallon Plate by Pivoting Subduction, *J. Geol.* **86**, 99–110.

Menard, H. W., 1984, Evolution of Ridges by Asymmetrical Spreading, *Geology* **12**, 177–180.

Menard, H. W., Chase, T. E., and Smith, S. M., 1964, Galapagos Rise in the Southeast Pacific, *Deep-Sea Res.* **11**, 233–244.

Miller, S. P. and Hey, R. N., 1986, Three-Dimensional Magnetic Modeling of a Propagating Rift, Galapagos 95°30′ W, *J. Geophys. Res.* **91**, 3395–3406.

Peirce, J. W., 1978, The Northward Motion of India since the Late Cretaceous, *Geophys. J.R. Astron. Soc.* **52**, 277–311.

Rea, D. K. and Dixon, J. M., 1983, Late Cretaceous and Paleogene Tectonic Evolution of the North Pacific Ocean, *Earth Planet. Sci. Letters* **65**, 145–166.

Sandwell, D. T., 1986, Thermal Stress and the Spacings of Transform Faults, *J. Geophys. Res.* **91**, 6405–6418.

Schouten, H. and Klitgord, K. D., 1982, The Memory of the Accreting Plate Boundary and the Continuity of Fracture Zones, *Earth Planet. Sci. Letters* **59**, 255–266.

Schouten, H. and White, R. S., 1980, Zero-Offset Fracture Zones, *Geology* **8**, 175–179.

Schouten, H., Klitgord, K. D., and Whitehead, J. A., 1985, Segmentation of Mid-Ocean Ridges, *Nature* **317**, 225–229.

Sclater, J. G. and Fisher, R. L., 1974, The Evolution of the East Central Indian Ocean, with Emphasis on the Tectonic Setting of the Ninetyeast Ridge, *Geol. Soc. Am. Bull* **85**, 683–702.

Searle, R. C. and Hey, R. N., 1983, Gloria Observations of the Propagating Rift at 95.5° W on the Cocos-Nazca Spreading Center, *J. Geophys. Res.* **88**, 6433–6448.

Sempere, J.-C. and Macdonald, K. C., 1966, Deep-Tow Studies of the Overlapping Spreading Centers at 9°03′ N on the East Pacific Rise, *Tectonics* **5**, 881–900.

Shih, J. and Molnar, P., 1975, Analysis and Implications of the Sequence of Ridge Jumps that Eliminated the Surveyor Transform Fault, *J. Geophys. Res.* **80**, 4815–4822.

Sleep, N. H. and Rosendahl, B. R., 1979, Topography and Tectonics of Mid-Oceanic Ridge Axes, *J. Geophys. Res.* **84**, 6831–6839.

Stein, S., Melosh, H. J., and Minster, J. B., 1977, Ridge Migration and Asymmetric Sea-Floor Spreading, *Earth Planet Sci. Letters* **36**, 51–62.

Tamaki, K. and Larson, R. L., 1988, The Mesozoic Tectonic History of the Magellan Microplate in the Western Central Pacific, *J. Geophys. Res.* **93**, 2857–2874

Vogt, P. R., Kovacs, L. C., Bernero, C., and Srivastava, S. P., 1982, Asymmetric Geophysical Signatures in the Greenland-Norwegian and Southern Labrador Seas and the Eurasia Basin, *Tectonophysics* **89**, 95–160.

Weissel, J. K. and Hayes, D. E., 1971, Asymmetric Seafloor Spreading South of Australia, *Nature* **231**, 518–521.

Weissel, J. K. and Hayes, D. E., 1974, The Australian-Antarctic Discordance: New Results and Implications, *J. Geophys. Res* **79**, 2579–2587.

Wilson, D. S., Hey, R. N., and Nishimura, C., 1984, Propagation as a Mechanism of Reorientation of the Juan de Fuca Ridge, *J Geophys Res* **89**, 9215–9225.

Wilson, J. T., 1965, A New Class of Faults and their Bearing on Continental Drift, *Nature* **207**, 343–347

Winterer, E. L., 1976, Anomalies in the Tectonics Evolution of the Pacific, in *The Geophysics of the Pacific Ocean Basin and its Margin, 19*, edited by G. H. Sutton *et al.*, pp. 269–280, AGU, Washington, D.C.