Earth and Planetary Science Letters, 96 (1990) 384–392
Elsevier Science Publishers B.V., Amsterdam – Printed in The Netherlands

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Kinematics of overlapping rift propagation with cyclic rift failure

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Received July 5, 1989; revised version received October 10, 1989

Existing kinematic models for propagation of oceanic spreading ridges that incorporate overlap between ridge segments fail to describe detailed observations of the failed segments. I present a new model which discards the assumption of steady state behavior of the failing rift, permitting inward curvature of both rift tips in the overlap region. The shape of an inward-curving failing rift must continuously change, but is assumed to cyclically return to its original shape by discrete inward ridge jumps. Other assumptions of symmetric spreading and uniform simple shear deformation between the overlapping rift tips are retained from previous models. Inward curvature of failed rift structures provides much better agreement with observations, and is consistent with tensile fracture theory. If the offset between ridge segments is small enough, the inward jumps of the failing rift will cut across deformed structures originally formed at the propagating tip, possibly generating seafloor fabrics that crosscut each other at nearly right angles. Observations of such structures near the Gorda Ridge can be explained by a model incorporating variable cyclicity of the failing rift.

1. Introduction

In the original formulation of the rules of plate tectonics, transform faults were assumed to be fixed relative to each other and the ridge segments they offset. The propagating rift model [1], which discards this assumption, has been very successful in describing oblique offsets in magnetic anomalies as a result of the lengthening of a ridge segment through time at the expense of the adjacent segment. Detailed observations of active propagating rifts suggest that the assumption that ridges are necessarily offset by discrete transform faults should also be discarded, with the segments instead offset by zones of distributed shear with widths of 10 or more km [2,3].

McKenzie [4] has proposed a kinematic model for formation and deformation of isochrons in such a system (Fig. 1). His model assumes uniform simple shear deformation in the shear zone, with associated linear gradients in spreading rate on the bounding rift tips. The parabolic curvature of the rift tips is derived from the assumptions of symmetric spreading and steady state ridge geometry. Several features of this model depart from Hey's [1] original model, which was based on discrete transforms. Along the outer pseudofault, isochrons curve inward toward the ridge, faithfully recording the shape of the propagating tip in an undeformed part of the plate. Isochrons also curve toward the ridge along the inner pseudofault, but

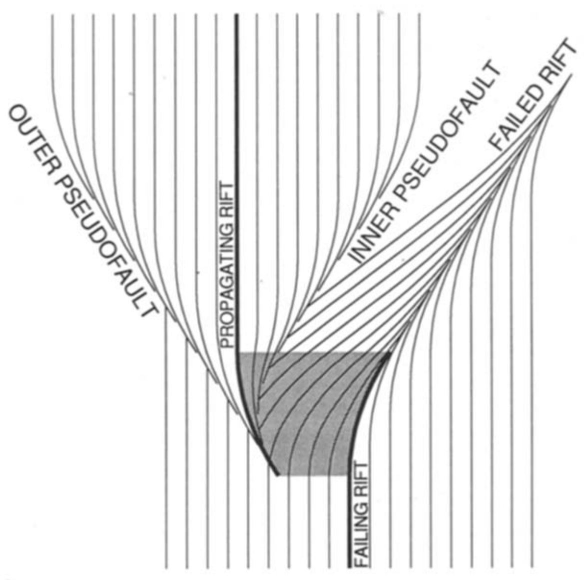

Fig. 1. Kinematic model after McKenzie [4] for steady state overlapping rift propagation. Bold lines denote active rift zones, and shading indicates the active shear zone between the two rift tips. Terminology follows Hey et al. [3].

0012-821X/90/$03.50

in this case the sense of curvature has been reversed from its original sense by deformation within the shear zone. Isochrons that were originally formed without curvature ahead of the shear zone show gradual curvature within the shear zone. The failing rift tip curves away from the propagating tip with a shape that is maintained by deflection of previously straight rift geometry by spreading at the propagating tip.

Many features of McKenzie's model are observed at active and fossil propagators. Curvature of the spreading fabric inside of the outer pseudofault is observed in most cases where there is adequate data coverage. In some cases, this curvature is readily visible in magnetic anomaly data [5–7]. Fabric near the inner pseudofault is often more difficult to map, but often can be interpreted as also curving in toward the ridge. Orientations of lineations in the shear zone at the well-surveyed propagator at 95.5° W show very striking agreement with the model [3]. The one prediction of the model that has not been observed is the outward curvature of the failing rift tip. Fig. 2 shows an isochron interpretation from one of the most dense magnetic data sets over an inner pseudofault–failed rift system, located in the central Juan de Fuca plate, northeast Pacific. Isochrons along the inner pseudofault do curve toward the ridge, and they overlap with their failed-rift counterparts by about 20–30 km. The curvature of the failed rift system, however, is opposite that predicted in Fig. 1. This paper addresses this discrepancy, proposing a revision of McKenzie's model with an alternative behavior of the failing rift.

The description of the failing rift is already recognized as the weakest aspect of the existing model, as rift failure appears to be much more episodic than rift propagation [3,4]. Many workers find the outward curvature of the failing rift bothersome, as it is opposite the curvature observed in the nontransform ridge offsets known as overlapping spreading centers, which generally show 180° rotational symmetry, with both rift tips curving inward [8,9]. Those ridges that curve approaching transform faults also always curve in the same sense. Inward curvature is observed at the tips of offset tensile fractures over a wide range of scales, and is a predictable consequence of the interaction of the stress fields of crack tips [10,11]. A more credible description of overlapping rift propagation should incorporate inward curvature of both rift tips.

2. Revised model

The McKenzie model derives the outward curvature of the failing rift from the steady state assumption. The new model presented here instead assumes an initial geometry of inward curvature of the failing rift. This inward curvature cannot be maintained, even with large degrees of asymmetric spreading, and the ridge geometry must change with time. The ridge behavior is assumed to be cyclic, with the failing tip repeatedly returning by discrete jumps to its initial geometry. McKenzie's other assumptions of steady state behavior of the propagating tip and of a shear zone with a linear velocity gradient are maintained. The time-dependent behavior following a discrete jump is governed by the symmetric spreading assumption.

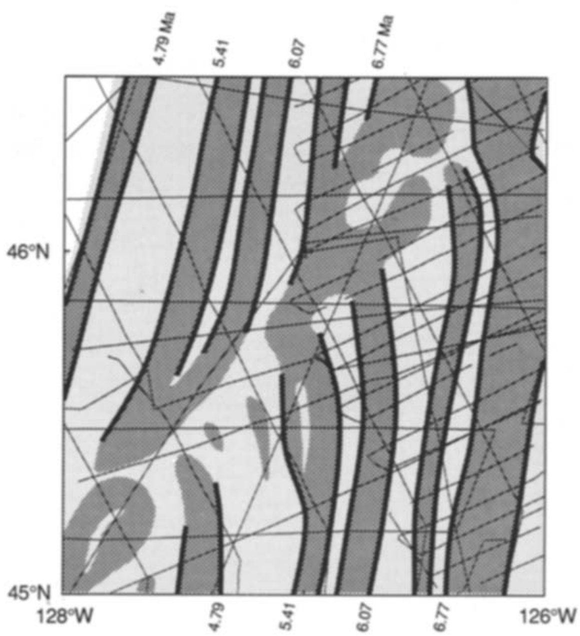

Fig. 2. Interpretation of magnetic polarity (darker shading = normal) and selected isochrons (bold lines, with indicated ages [24]) from the central Juan de Fuca plate, based on magnetic anomaly data along the indicated ship's tracks (thin lines). The diagonal offset across the center of the figure has been interpreted to be the inner pseudofault and failed rift of a propagating rift [1,25], here interpreted as overlapping. Northwest of the offset, isochrons curve toward younger ages as predicted in figure 1, but to the southeast, the curvature is opposite that predicted for failed rifts.

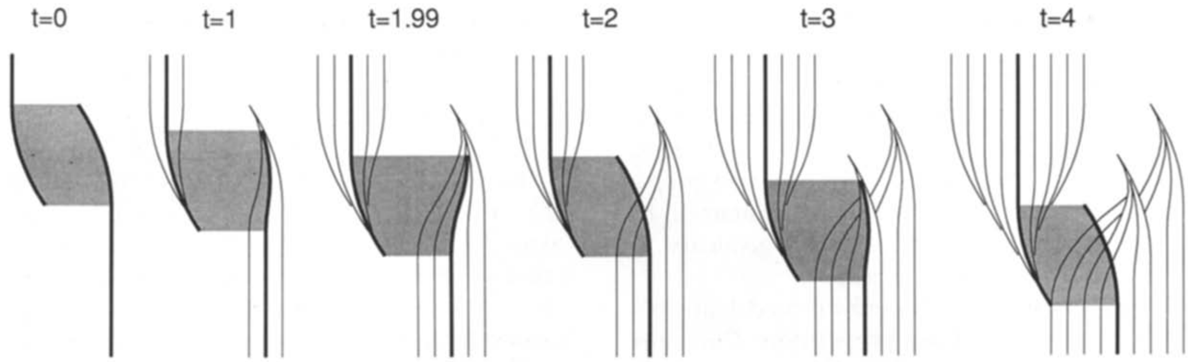

Fig. 3. Step-by-step evolution of the proposed nonsteady revision of McKenzie's model. The initial geometry has both rift tips curving inward, as observed at many overlapping rift offsets. Deflection of the failing rift is governed by assuming symmetric spreading as the amount of material between the two rift tips increases. Periodically, the failing rift returns to its initial geometry by discrete ridge jumps.

In contrast to the analytical formulation by McKenzie [4], the models presented here are based on computer simulation of the spreading history, keeping track of individual points on isochrons and moving them through time based on integration of the velocity history at each point. The

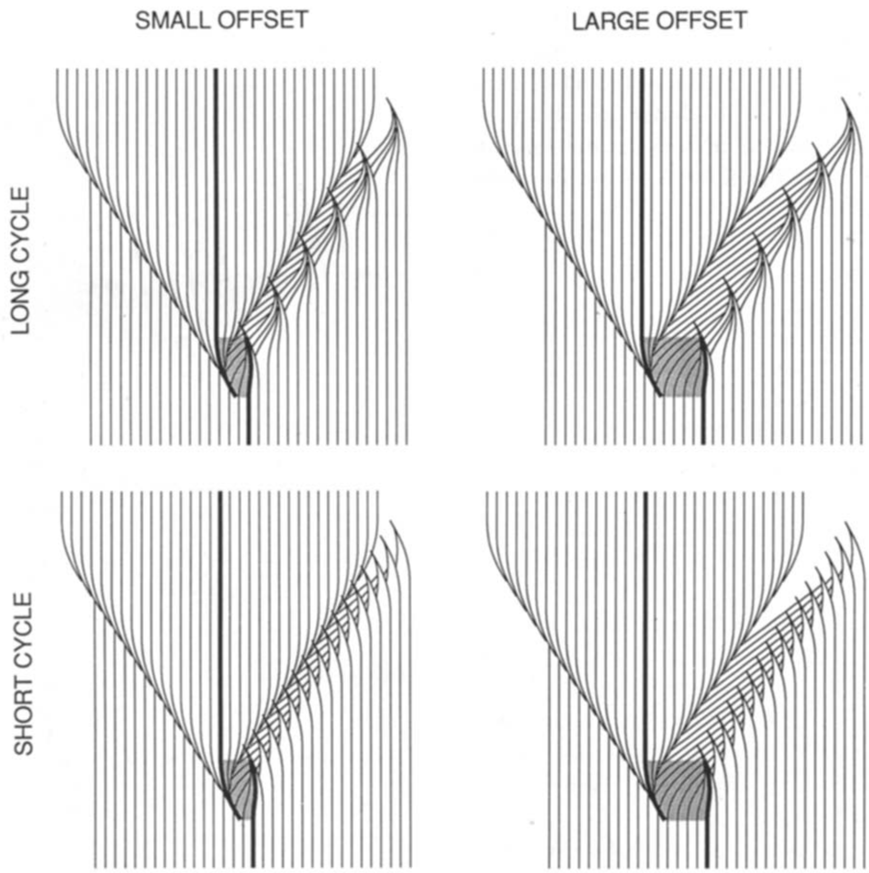

Fig. 4. Isochron geometries predicted for multiple stable cycles of the model of Fig. 3, showing the effects of varying ridge offset and cycle length.

propagating tip is parabolic, with the curvature tangent to the outer pseudofault at the tip, as specified by McKenzie. Without constraining the failing tip to have steady state geometry, its shape at the time of a jump is a free parameter; for convenience, these models also use a parabolic curve.

Stepwise evolution of the new model in its simplest form is shown in Fig. 3. For simplicity, the initial curvature of the failing tip is the same as that of the propagating tip. Symmetric spreading within the shear or overlap zone deflects the failing tip outward, and the part of the failing tip that was originally straight acquires exactly the curvature of the McKenzie model. After a certain degree of outward curvature has been obtained, the entire failing rift within the shear zone becomes inactive and a new rift forms with the original degree of curvature within the shear zone. This style of inward ridge jump has been termed "self-decapitation" by Macdonald et al. [12]. The physical significance of this reorganization is presumably that the inward curvature of the stress trajectories governed by the overlap of the rift tips eventually overcomes the tendency of dikes to follow the zone of weakness left by previous dikes. The simplest case of such a model is purely periodic behavior, with regular intervals between inward jumps of the failing rift.

Fig. 4 shows the geometries predicted by periodic models, with the overlap/offset ratio and the length of the cycle varied between models. For larger offsets, the inward jumps of the failing rift cut across only material formed along the failing segment. At smaller offsets, the inward jumps can cut across the inner pseudofault into material formed at the propagating segment. In general, the fabrics formed at the separate tips where offset is smaller than overlap will cut across each other at high angles. If jumps of the ridge are very frequent, our ability to observe them may be limited by the intervals between formation of the major faults that comprise the spreading fabric. In contrast, if the failing rift jumps less frequently and has a graben morphology, each separate jump of the failing rift should produce an easily observable inward-curving graben.

The failed rift system in Fig. 2 appears to have frequent jumps, although the basement fabric is obscured by sediment. The propagator at 95.5°W

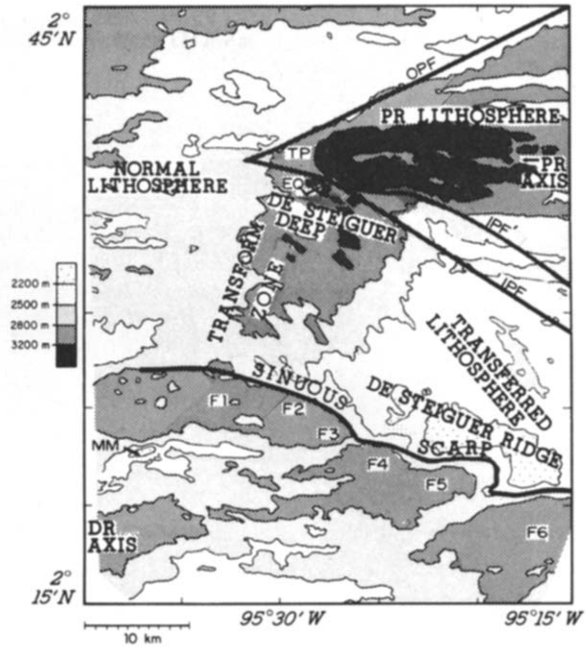

Fig. 5. Tectonic interpretation superimposed on bathymetry for the 95.5°W propagator, from Hey et al. [3]. *PR* = propagating rift; *OPF* = outer pseudofault; *IPF*, *IPF* = alternative interpretations for inner pseudofault; *F*1–*F*6 = grabens in the failing/failed rift system. The undulations in "sinuous scarp" are interpreted as resulting from discrete northward jumps of the failing rift tip.

[3] probably falls into the latter category of more infrequent jumps. A major bathymetric feature in the area of the failed rift zone has been termed "sinuous scarp" (Fig. 5). This scarp has been interpreted as the southern limit of uplifted material of the zone of transferred lithosphere, although the mechanism of uplift remains under debate [3,13]. The sinuousities of the scarp can easily be interpreted as encircling separate failed rift grabens as in Fig. 4. Lack of recognizable inward curvature on the failing rift tip may indicate a relatively long time interval since its last jump, as in the $t = 1.99$ step of Fig. 3. Two recently surveyed propagators at 87.5°W (Galapagos) [14] and 15°N (East Pacific Rise) [15] do not show graben morphology of the failed rifts, but agree with the geometry predicted for frequent jumps of the inward-curving failed rift.

3. Application of the model to the northern Gorda Ridge

GLORIA side-scan sonar images collected near the northern Gorda Ridge [16] indicate basement

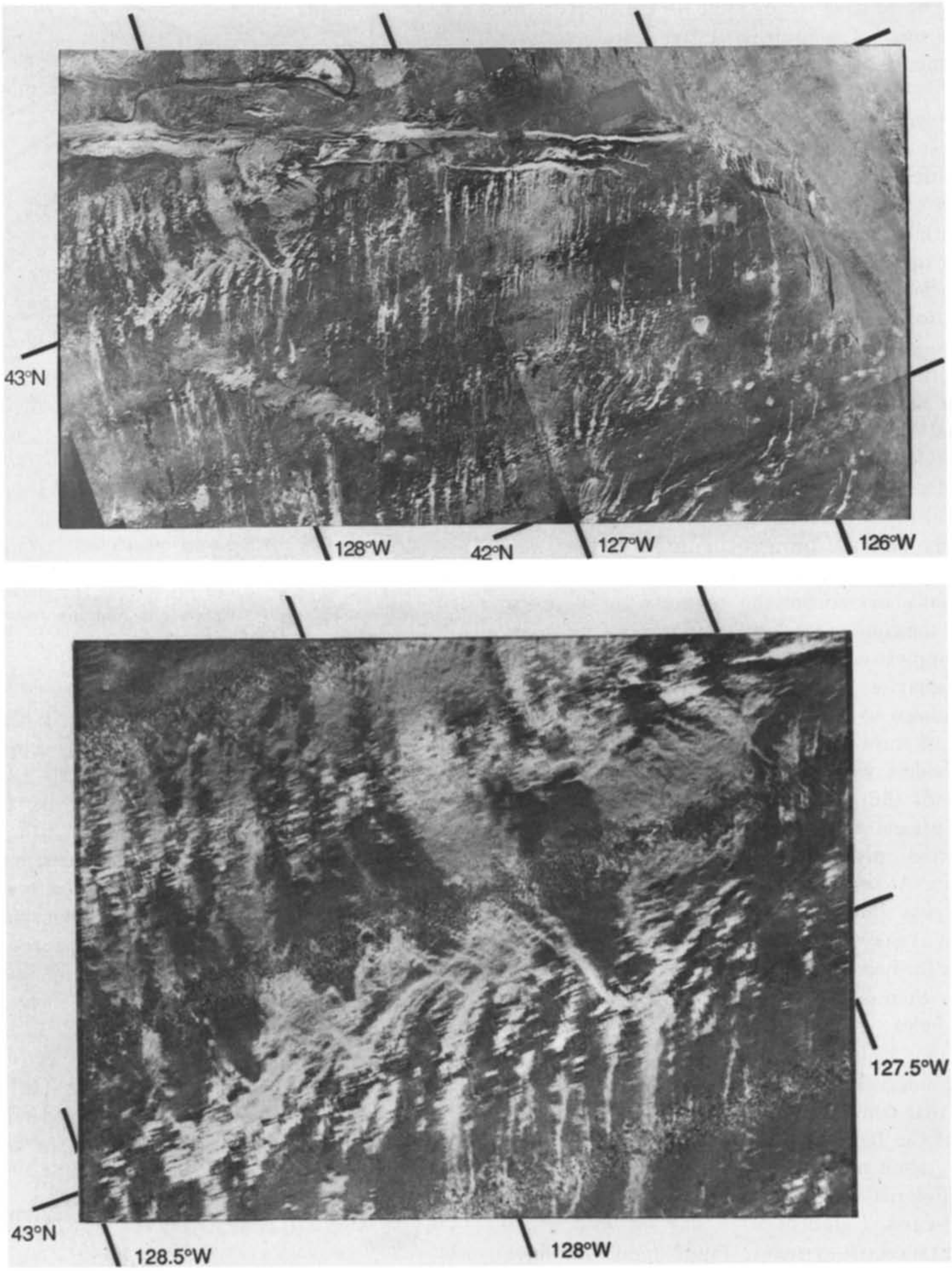

Fig. 6. Top: GLORIA side-scan sonar mosaic of the northern Gorda Ridge and eastern Blanco Fracture Zone, northeast Pacific [16]. Bottom: Enlargement showing structures interpreted as resulting from failing rift jumps.

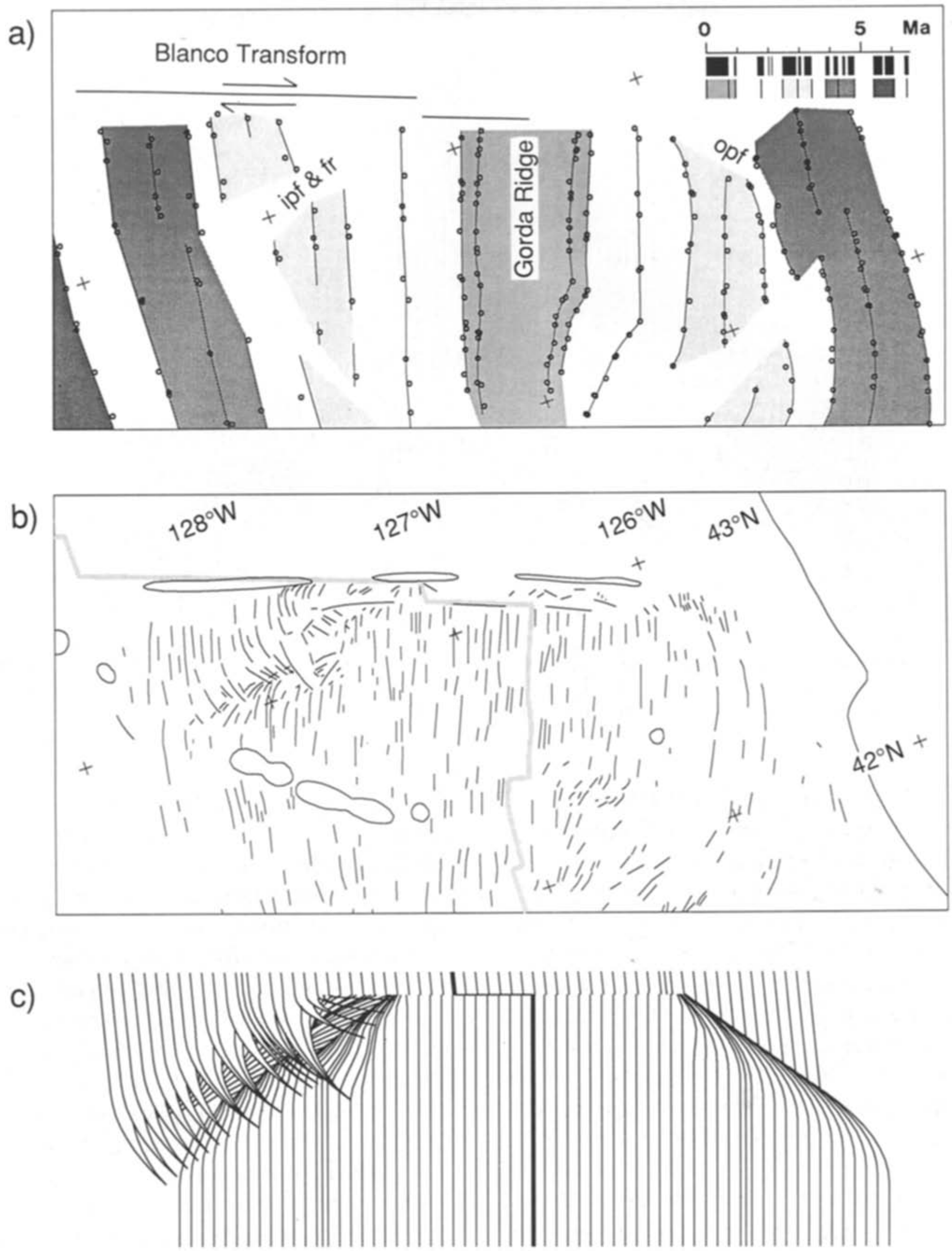

Fig. 7. (a) Isochrons interpreted from magnetic anomalies for the northern Gorda Ridge [18]. (b) Basement lineations interpreted from GLORIA images [16]. (c) Isochron model for the observed geometry, assuming variations in the cyclic behavior of the failing rift. See Fig. 8 for the evolution of model.

trends showing many similarities to the models presented in Fig. 4 (Figs. 6 and 7). The oblique offsets of the spreading fabric and magnetic anomalies indicate a period of northward propagation of the Gorda Ridge during the interval 4–2 Ma, producing a ~ 15° clockwise reorientation of the ridge axis. This propagation has been interpreted as a response to a change in Juan de Fuca–Pacific relative plate motion at 5 Ma [6]. Of particular interest is the area west of the ridge

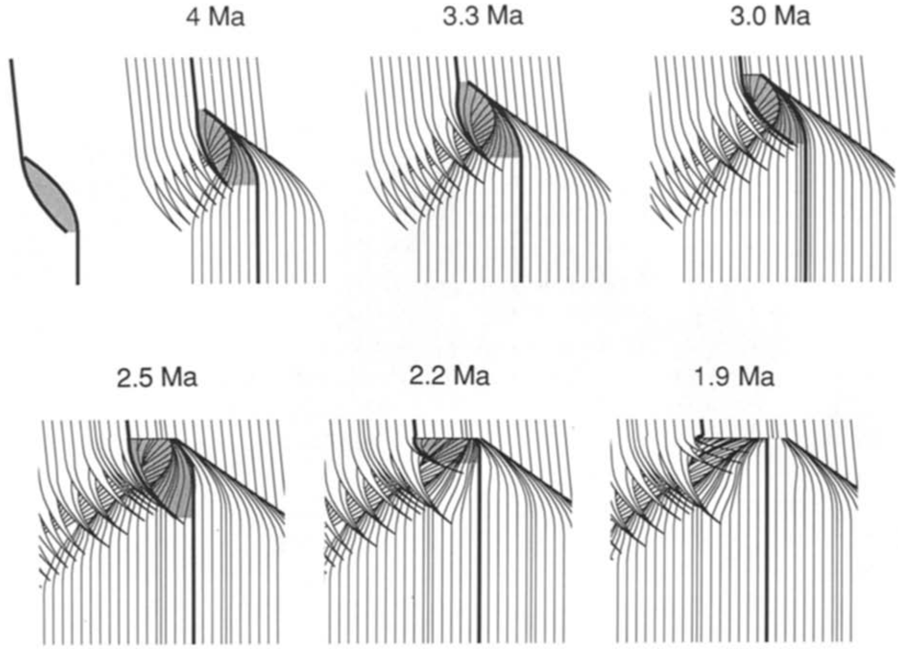

Fig. 8. Step-by-step evolution of the model of Fig. 7c. Model steps are by distance rather than by time; the indicated ages are approximate. The shear zone reaches its northern limit at about 3.1 Ma and begins to form a discrete transform. There is a temporary increase in the width of the shear zone near 2.5 Ma. See text for further discussion.

near 43° N, 128° W, where there are two groups of cross-cutting lineations curving in toward the ridge, similar to the small-offset cases in Fig. 4.

The model presented in Figs. 7c and 8 attempts to simulate the observed geometry using the model behavior of Fig. 3. Not surprisingly, the details of the basement fabric require a more complex ridge behavior than exhibited by the simple cyclicity of Figs. 3 and 4. Necessary complexities required for the model to show reasonable agreement with the data include variation in the curvature of the failing rift and variation of the interval between jumps of the failing rift.

Fig. 8 shows selected steps in the model evolution. The model increments in steps of constant spreading distance (4.8 km) and maintains a constant ratio of propagation rate to half-spreading rate (0.7, which is exceptionally low). As the half-spreading rate has decreased from about 40 km/Myr to 28 km/Myr since 5 Ma [17,18], the duration of each step ranges over about 0.12–0.17 Myr. The initial width of the shear zone is 38 km, measured perpendicular to spreading direction. The initial geometry and pre-4 Ma evolution of the model are not supported in any detail by data, but schematically show a gradual increase in ridge offset and establishment of orthogonal spreading on the propagating ridge segment. From 4 to 3.3 Ma, the model demonstrates the relatively long (~ 0.3 Myr) interval between recognizable jumps of the failing rift. By 3.0 Ma, jumps of the failing rift had become much more frequent.

As this propagator approached the existing Blanco transform, the offset was not added to the existing transform but instead formed a new en echelon segment of the transform system [19]. The exact mechanism and timing of the conversion from overlapping propagator to stable transform fault are not obvious, but the process was complete by 1.8 Ma. This transition is modeled by establishing a northern limit to the propagation of the shear zone, and accumulating any shear displacement that would otherwise occur north of the limit as slip along a discrete fault. This process has just begun in the 3.0 Ma reconstruction in Fig. 8.

An additional complexity required for the model to describe the basement fabric data is variability in the degree of overlap. There is a deep graben (~ 3900 m maximum water depth) at 127.8° W between 43.0° N and 43.25° N. This graben cuts across the inner pseudofault in the fashion proposed for failed rifts, but extends at least 15 km farther than the immediately older failed rift structures. This increased overlap is shown in the 2.5 Ma reconstruction. The change in overlap and therefore rate of shear implies that either the propagating tip must change shape or spread asymmetrically; as implemented here the shape remains constant unless that would cause asymmetry to exceed 50%. The increase in the amount of overlap seems to have been temporary, as there is no evidence for failed rift structures east of 127.5° W. The reconstructions for 2.2 and 1.9 Ma show the shear zone contracting rapidly. The cause of cessation of propagation and formation of a new transform segment is not known, but is perhaps related to lower temperature and therefore greater strength of the lithosphere close to the fracture zone.

4. Discussion

The assumption that both propagating and failing rift tips curve inward toward each other can lead to models that successfully describe previously enigmatic failed rift geometry. This assumption requires cyclic rather than steady state behavior, but does not require unreasonable complexity. The success of this type of model further blurs the distinction between propagating rifts as identified by Hey and others [1–3], and overlapping rift zones described by Macdonald, Lonsdale, and others [8,9,12].

There does seem to be one sense where it is meaningful to maintain a distinction between the two types of offset. Standard propagating rifts could be distinguished by a continuous outer pseudofault, produced by steady state behavior of the propagating tip. Most propagators from the northeast Pacific and the Galapagos Spreading Center can be placed in such a category. Stable behavior of the propagating tip appears to be much less common along the East Pacific Rise, where spreading rates are generally faster. For example, the offset at 20° S has migrated southward about 60 km since 1.8 Ma [20]. Detailed observations of this offset [21] indicate that both rift tips have had unsteady behavior, with repeated discrete jumps at both tips. Multiple jumps of the tip more closely resembling the propagating tip would produce a discontinuous outer pseudofault with an interfingering texture not unlike the failed rifts in Fig. 4. Other overlapping offsets, for instance at 2.8° S [22], show much less tendency to migrate in a constant direction and show frequent jumps of both rift tips. Extending the type of modeling presented in this paper to incorporate nonsteady behavior of both tips could provide a valuable tool for interpreting the history of complex offsets.

This study has emphasized kinematic considerations with little regard for the underlying dynamics. Forward modeling has been used as a tool to support an interpretation of the history of the ridge geometry inferred from the spreading fabric. The philosophical justification for ignoring physics at this stage is that it is prudent to reach a reasonable consensus as to what has happened before devoting too much effort to why it happened that way. If the interpretations proposed above are correct, extreme weakness of young (less than about 0.5 Myr) oceanic lithosphere is likely to be a necessary feature of a complete dynamic interpretation. Evidence for such weakness would include the tendency of the shear zone to migrate into young, but previously unsheared lithosphere, and the tendency of the failing rift to jump from the site of most recent intrusion into the slightly older lithosphere of the shear zone. Such weakness is quite plausible if the base of near-axis lithosphere is defined by ductile failure of gabbroic rocks at about 500°C, as proposed by Tapponnier and Francheteau [23].

Acknowledgements

Discussions with Jeff Severinghaus, Laura Perram, Ken Macdonald, and Tanya Atwater helped clarify several of the ideas presented in this paper. Supported by NSF grant OCE88-11061.

References

1 R.N. Hey, A new class of pseudofaults and their bearing on plate tectonics: a propagating rift model, Earth Planet. Sci. Lett. 37, 321–325, 1977.

2 R.N. Hey, F.K. Dunnebier and W.J. Morgan, Propagating rifts on mid-ocean ridges, J. Geophys. Res. 85, 3647–3658, 1980.

3 R.N. Hey, M.C. Kleinrock, S.P. Miller, T.M. Atwater and R.C. Searle, Sea Beam/deep-tow investigation of an active

oceanic propagating rift system Galapagos 95.5° W, J. Geophys. Res. 91, 3369–3393, 1986.
4 D. McKenzie, The geometry of propagating rifts, Earth Planet. Sci. Lett. 77, 176–186, 1986.
5 H.P. Johnson, J. Karsten, J.R. Delaney, E.E. Davis, R.G. Currie and R.L. Chase, A detailed study of the Cobb offset of the Juan de Fuca Ridge: evolution of a propagating rift, J. Geophys. Res. 88, 2297–2315, 1983.
6 D.S. Wilson, Tectonic history of the Juan de Fuca ridge over the last 40 million years, J. Geophys. Res. 93, 11863–11876, 1988.
7 P. Lonsdale, Structural patterns of the Pacific floor offshore of Peninsular California, Am. Assoc. Pet. Geol. Mem. 47, in press, 1989.
8 K.C. Macdonald and P.J. Fox, Overlapping spreading centres: new accretion geometry on the East Pacific Rise, Nature 302, 55–57, 1983.
9 P. Lonsdale, Overlapping rift zones at the 5.5° S offset of the East Pacific Rise, J. Geophys. Res. 88, 9393–9406, 1983.
10 D.D. Pollard and A. Aydin, Propagation and linkage of oceanic ridge segments, J. Geophys. Res. 89, 10017–10028, 1984.
11 J.-C. Sempere and K.C. Macdonald, Overlapping spreading centers: implications from crack growth simulations by the displacement discontinuity method, Tectonics 5, 151–163, 1986.
12 K.C. Macdonald, J.-C. Sempere, P.J. Fox and R.C. Tyce, Tectonic evolution of ridge axis discontinuities by the meeting, linking, or self-decapitation of neighboring ridge segment, Geology 15, 993–997, 1987.
13 J. Phipps Morgan and E.M. Parmentier, A three-dimensional gravity study of the 95.5° W propagating rift in the Galapagos Spreading Center, Earth Planet. Sci. Lett. 81, 289–298, 1987.
14 L.J. Perram and K.C. Macdonald, An overlapping propagating center at 87°30′W on the Galapagos Spreading Center (abstract), EOS, Trans. Am. Geophys. Union 69, 1425, 1988.
15 J.A. Madsen, D.J. Fornari, M.H. Edwards, D.G. Gallo, M.R. Perfit and A.N. Shor, Kinematic framework of the Cocos-Pacific plate boundary between 12°50′N and 15°10′N: Results from an extensive magnetic and Sea MARC II survey (abstract), EOS, Trans. Am. Geophys. Union 69, 1478, 1988.
16 EEZ-SCAN 84 Scientific Staff, Atlas of the Exclusive Economic Zone, Western Conterminus United States, U.S. Geol. Surv. Misc. Invest. Ser. I-1792, 152 p, scale 1 : 500,000, 1986.
17 R.P. Riddihough, Gorda plate motions from magnetic anomaly analysis, Earth Planet. Sci. Lett. 51, 163–170, 1980.
18 D.S. Wilson, Deformation of the so-called Gorda plate, J. Geophys. Res. 94, 3065–3075, 1989.
19 R.W. Embley, D.S. Wilson, A. Malahoff and R. Ganse, Tectonics of the Blanco transform, Northeast Pacific, Mar. Geophys. Res., submitted, 1988.
20 D.K. Rea, Asymmetric seafloor spreading and a nontransform axis offset: the East Pacific Rise 20° S survey area, Geol. Soc. Am. Bull. 89, 836–844, 1978.
21 K.C. Macdonald, R. Haymon, S.P. Miller, J.-C. Sempere and P.J. Fox, Deep-tow and Sea Beam studies of dueling propagating ridges on the East Pacific Rise near 20°40′S, J. Geophys. Res. 93, 2875–2898, 1988.
22 P. Lonsdale, The rise flank trails left by migrating offsets of the equatorial East Pacific Rise, J. Geophys. Res. 94, 713–743, 1989.
23 P. Tapponnier and J. Francheteau, Necking of the lithosphere and the mechanics of slowly accreting plate boundaries, J. Geophys. Res. 83, 3955–3970.
24 G. Ness, S. Levi and R. Couch, Marine magnetic anomaly timescales for the Cenozoic and Late Cretaceous: a precis, critique, and synthesis, Rev. Geophys. Space Phys. 18, 753–770, 1980.
25 D.S. Wilson, R.N. Hey and C. Nishimura, Propagation as a mechanism of reorientation of the Juan de Fuca Ridge, J. Geophys. Res. 89, 9215–9227, 1984.