Episodic triple-junction migration by rift propagation and microplates

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ABSTRACT

We describe a model for episodic, open-ocean triple-junction migration based on observations of actual triple-junction evolutions. Migration progresses by repeated episodes of rift propagation, microplate formation, and microplate accretion to an adjacent, larger plate. These episodes may be highly variable in space and time depending on triple-junction geometry, velocity triangle, and other factors affecting local thermal and rheological conditions. Resulting tectonic features may include an abandoned transform fault, straight and potentially curving pseudofaults, sheared and potentially rotated abyssal-hill fabric, and a paleomicroplate with no associated failed rift. This model, developed mainly from the evolution of the Pacific-Antarctic-Nazca triple junction, may be relevant for other types of triple junctions such as the Bouvet and Azores triple junctions and ridge-ridge-ridge triple junctions in the Indian and Pacific Oceans. Episodic migration is found to occur even when the triple junction is kinematically stable. This model highlights the difference between predicted kinematic stability of triple junctions and observations of their true tectonic history.

INTRODUCTION

Since the classic work of McKenzie and Morgan (1969), triple-junction "stability" has been considered mainly in terms of the kinematic ability of a triple junction to remain unchanged in its geometry as a function of time (e.g., Patriat and Courtillot, 1984). However, Cronin (1992) pointed out that most triple junctions are probably unstable most of the time, and suggested that their evolution is best studied using empirical data rather than kinematic models that assume constant or circular finite relative motion across plate boundaries. In this paper we examine a number of kinematically stable triple junctions that do not retain a steady-state geometry but exhibit histories of episodic migration involving rift propagation and the formation and eventual accretion of microplates to larger plates. These observations lead us to reevaluate the significance of triple-junction kinematic stability.

Sea-floor spreading plate boundaries commonly reorganize via rift propagation (e.g., Hey, 1977; Hey et al., 1995), and microplates tend to play a key role in large-scale plate boundary reorganizations (e.g., Hey et al., 1985; Naar and Hey, 1991; Bird et al., 1998). Reasons for reorganization appear to be varied and include changing relative or absolute plate motions, elevated ridge-axis depth, and transform shear (e.g., Hey et al., 1989, 1995). Although triple-junction migration and complex plate boundary interactions are known to occur, they are poorly understood in detail, especially when they occur contemporaneously. To increase this understanding, we examine the tectonic history of the Pacific-Antarctic-Nazca triple junction, which includes the Friday paleomicroplate (formerly at the Pacific-Antarctic-Nazca triple junction and involved in a triple-junction migration event ca. 12 Ma) and the Juan Fernandez microplate (located between the three large plates). The most recent magnetic anomaly interpretations and plate tectonic reconstructions for these areas provide the primary evidence for the proposed triple-junction migration model (Tebbens and Cande, 1997; Bird et al., 1998). We also examine other triple junctions to test the model's applicability.

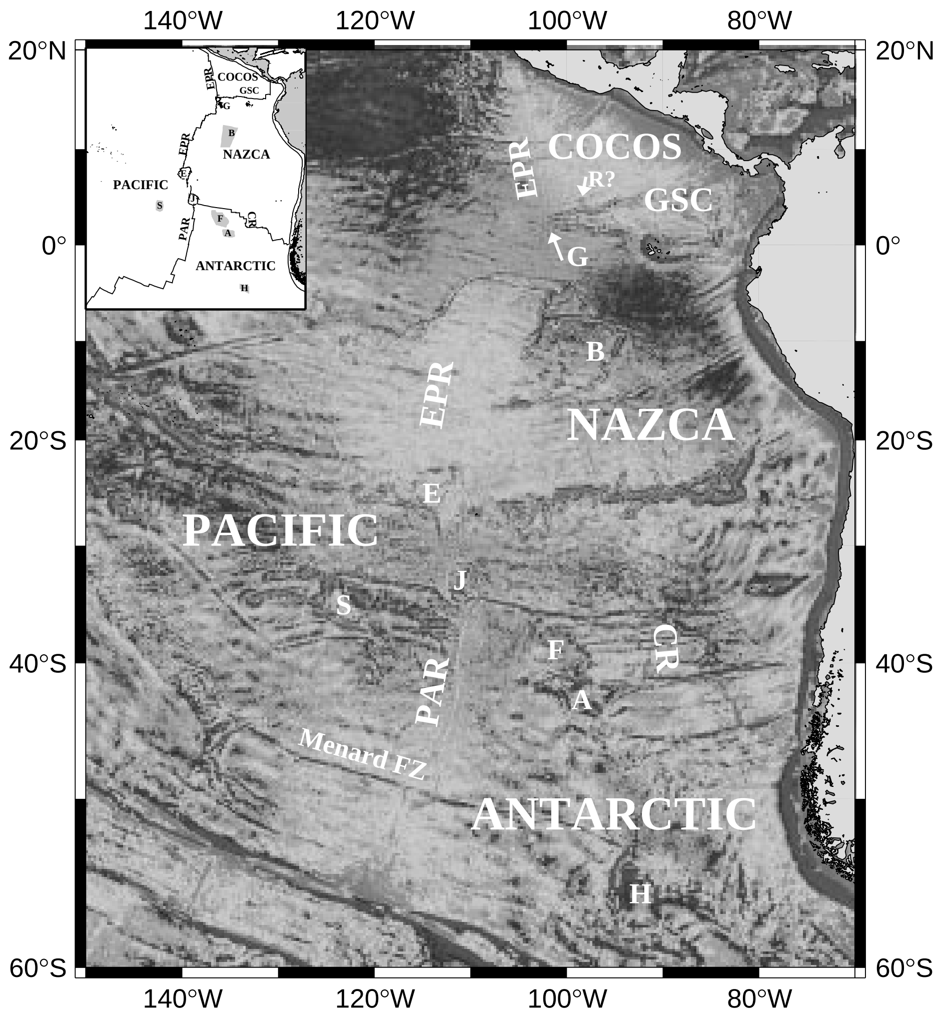

Figure 1. Satellite-derived gravity field of southeast Pacific (Sandwell and Smith, 1997). Major plates—Pacific, Antarctic, Nazca, and Cocos—and their plate boundaries—East Pacific Rise (EPR), Pacific-Antarctic Ridge (PAR), Chile Ridge (CR), and Galapagos spreading center (GSC)—are labeled. Active Juan Fernandez microplate (J) at Pacific-Antarctic-Nazca triple junction, Easter microplate (E), and Galapagos microplate (G) at Pacific-Nazca-Cocos triple junction are shown. Paleomicroplates associated with past triple-junction migrations include Friday microplate (F), probable microplate south of Friday (A), and Hudson microplate (H). Possible relic scar in Galapagos region is denoted by R?. Selkirk (S) and Bauer (B) paleomicroplates were not associated with triple-junction migrations. Inset shows same region; plate boundaries are solid lines.

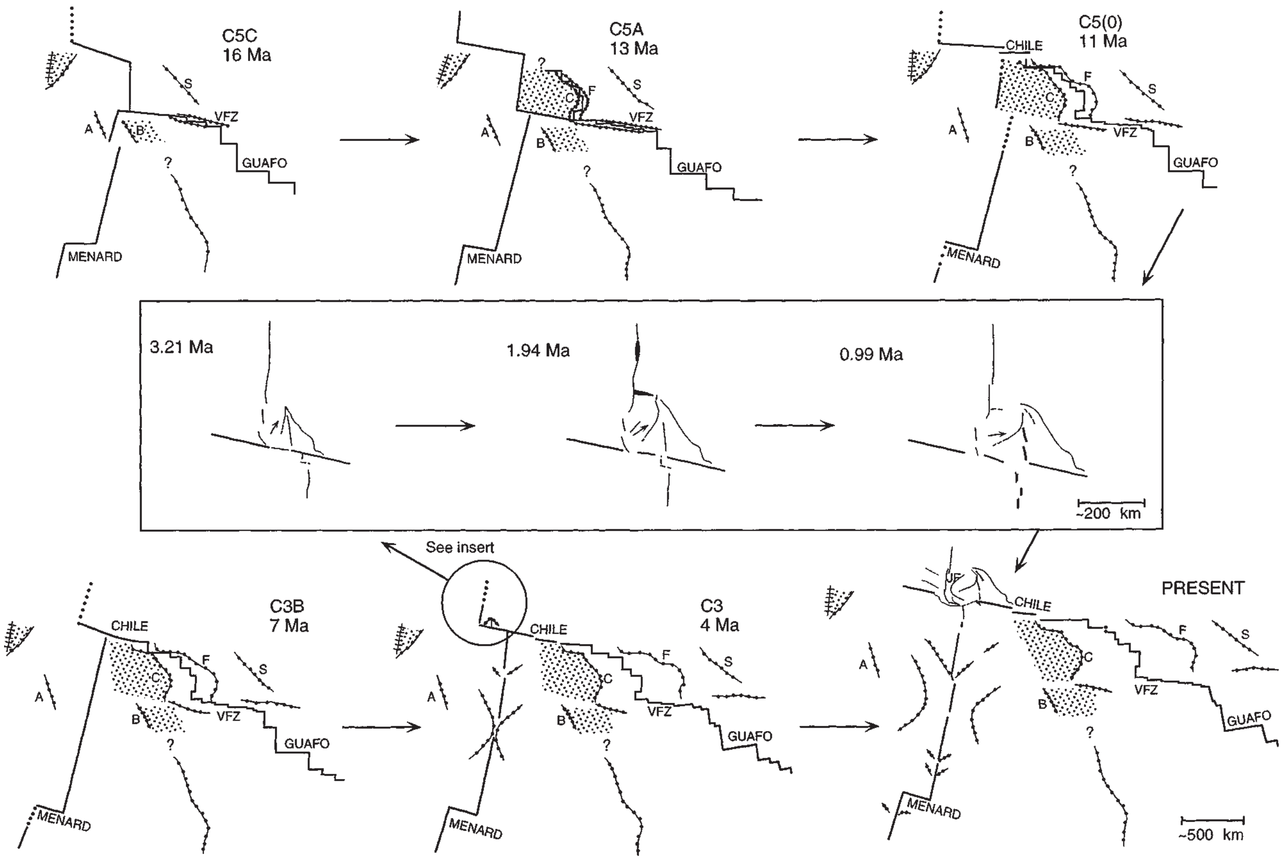

Figure 2. Detailed evolution of Pacific-Antarctic-Nazca triple junction since 16 Ma (modified from Tebbens and Cande, 1997). Prior to that time, ridge-ridge-ridge triple junction had been migrating northward in smooth, continuous manner. Subsequently, triple junction migrated from Valdivia fracture zone (VFZ) to Chile transform by episodic triple-junction migration including ridge propagation, microplate formation, and microplate abandonment. Inset shows similar sequence of events at present triple junction, where rift propagation formed Juan Fernandez microplate (JF; modified from Bird et al., 1998). Scale bars are approximate; maps use Mercator projection so distance varies as function of latitude. Abbreviations as in Figure 1.

PACIFIC-ANTARCTIC-NAZCA TRIPLE-JUNCTION EVOLUTION

Cande et al. (1982) first recognized that microplates play a role in triple-junction migration. They showed that at chron 21 time (ca. 46 Ma), the Hudson microplate (Fig. 1) changed the Pacific-Antarctic-Farallon-Aluk plate boundary with the extinction of two triple junctions and the formation of two new triple junctions. Tebbens and Cande (1997) showed that at chron 5A time (12 Ma), the formation and death of the Friday microplate enabled a 500 km northward migration of the Pacific-Antarctic-Nazca triple junction. In addition, a prior migration event occurred at chron 6 old time (20 Ma). Thus, the Pacific-Antarctic-Nazca triple junction and its predecessor, the Pacific-Antarctic-Farallon triple junction, have an ~46 m.y. history of northward migration, leaving a legacy of fossil microplates embedded in the Antarctic plate (Tebbens and Cande, 1997). At present, another migration event may be in progress at the Juan Fernandez microplate (Fig. 1; Bird et al., 1998). This region—where sea-floor spreading rates are currently the fastest on the planet (~150 km/m.y)—appears to be characterized by plate boundary instability (Naar and Hey, 1989; Bird and Naar, 1994; Hey et al., 1995).

Between chron 3A and chron 3 time (ca. 5.8 Ma), the Juan Fernandez microplate began to form by rift propagation from within a Pacific-Nazca transform fault (Fig. 2), likely in response to a change in spreading direction (Bird and Naar, 1994). Rift propagation continued on the nascent East Ridge and dominated the microplate's early history (Bird et al., 1998), capturing Nazca plate lithosphere to form the microplate core. East Ridge propagation also resulted in the northward migration of both the microplate's northern boundary and the Pacific–Juan Fernandez–Nazca triple junction.

Until about 2.6 Ma, the microplate was bordered by the Pacific and Nazca plates, but at this time, relative plate motions and microplate growth dictated that the Pacific-Antarctic-Nazca triple junction migrate westward along the Chile transform, placing the Antarctic plate next to the southeastern microplate edge (Larson et al., 1992; Kleinrock and Bird, 1994; Bird et al., 1998). The microplate entered the second phase of its history (Larson et al., 1992; Bird et al., 1998) in which northward East Ridge propagation slowed considerably, and sea-floor spreading on the microplate's bounding ridge axes dominated its growth. With the advent of edge-driven microplate rotation (Schouten et al., 1993), the southern boundary changed from a transform fault into a zone dominated by compression. A complex evolution of the southern microplate boundary followed (Kleinrock and Bird, 1994; Bird et al., 1998). At the southwestern boundary in particular, an episode of southward West Ridge propagation between ca. 1.8 and 1.1 Ma resulted in the accretion of both Pacific lithosphere and the newly abandoned southwestern boundary to the Juan Fernandez microplate; a reactivated fracture zone to the south became the new southwestern boundary. This entire process migrated the Pacific–Juan Fernandez–Antarctic triple junction southward (Bird et al., 1998) and provides a small-scale example of episodic triple-junction migration.

What does the future hold for the Juan Fernandez microplate? On the basis of migration history, it appears likely that the microplate will accrete to the Antarctic plate, allowing the Pacific-Antarctic-Nazca triple junction to complete another northward jump (Weissel et al., 1977;

Larson et al., 1992; Tebbens and Cande, 1997; Bird et al., 1998). Westward motion of the Pacific-Antarctic ridge crest relative to the microplate's West Ridge suggests that this accretion may occur in about 1 m.y., when both ridge axes align. In this scenario, the East Ridge would become a northern segment of the Chile Rise, and the West Ridge would assume Pacific-Antarctic spreading vectors.

OTHER TRIPLE-JUNCTION GEOMETRIES AND MIGRATION PATTERNS

Triple junctions are commonly thought to leave continuous linear traces on one or more plates marking their path through space and time. As shown here, this is not observed for the Pacific-Antarctic-Nazca triple junction, which maintains a kinematically stable, ridge-fault-fault geometry provided the two transform faults remain collinear (McKenzie and Morgan, 1969). The triple junction has been kinematically stable, in general, yet it has jumped northward repeatedly, perhaps due to small plate motion perturbations that led to rift propagation and microplate formation (e.g., Bird and Naar, 1994). The three migrations since 25 Ma were synchronous with plate boundary reorganizations throughout the Pacific Ocean (Tebbens and Cande, 1997).

Two distinct triple-junction traces exist on the Cocos and Nazca plates that are rough-smooth boundaries (Menard, 1967) related to the kinematically stable, ridge-ridge-ridge, Pacific-Cocos-Nazca triple junction. At least two areas along these traces exhibit a sharp bend or display adjacent rough bathymetry visible in the predicted bathymetry maps of Smith and Sandwell (1997). Some of these irregularities may be a result of rift propagation and/or microplate formation (e.g., altimetry anomaly shown in Fig. 1). At present, the active Galapagos microplate occupies the triple junction (e.g., Lonsdale, 1988). The Hess Deep, part of the Galapagos microplate, is an example of one of the many possible tectonic structures that may be abandoned along the triple-junction trace.

Likewise, the Bouvet triple junction (South America–Antarctica–Africa; e.g., Kleinrock and Phipps Morgan, 1988) may have left paleomicroplates during its history. Recent studies indicate that episodic rift propagation and lithospheric capture are occurring there, although the causal mechanism for propagation may be a major magmatic event (Ligi et al., 1997; Mitchell and Livermore, 1998) rather than a plate motion change.

Nakanishi and Winterer (1998) showed several episodes of rift propagation and microplate formation associated with Pacific-Farallon-Phoenix triple-junction evolution from Late Jurassic to Early Cretaceous time. Their Figure 10 shows a ridge-fault-fault triple junction at chron M22 (149 Ma) that evolved into the Trinidad microplate by chron M20. By chron M15, several rifts propagated near this microplate, one of which formed the Magellan microplate (Tamaki and Larson, 1988). By chron M0 (120 Ma), both microplates became attached to the Pacific plate (Joseph et al., 1993), and the triple junction acquired a ridge-ridge-ridge geometry and "jumped southward" (Nakanishi and Winterer, 1998).

Searle's (1980) preferred model for Azores triple-junction evolution (North America–Europe–Africa) indicates that its northward migration since 36 Ma was episodic and involved a new rift zone (the Terceira rift) and the eventual transfer of lithosphere from the European plate to the African plate. Migration may have responded to plate motion changes (Searle, 1980), although, like Bouvet, a hotspot is in close proximity. Work by Freire Luis et al. (1994) suggests that episodic migration of the Azores triple junction has occurred over the past 10 m.y. High-resolution studies of the Indian Ocean triple junction (Africa-Antarctica-India) also show that its recent evolution has involved rift propagation and lithospheric capture (Mitchell, 1991; Honsho et al., 1996). A final example of episodic rift propagation and microplate activity may be found at the Afar triple junction (Nubia-Somalia-Arabia), where a propagating continental rift has formed the Arabian microplate (Acton et al., 1991).

MODEL OF EPISODIC TRIPLE-JUNCTION MIGRATION

On the basis of our observations and published work, we advance a generalized model for open-ocean triple-junction migration involving the fundamental processes of rift propagation, microplate development, and lithospheric capture. This model allows for, but does not require, periods of episodic triple-junction migration. Furthermore, we cannot predict on which of the three major plates a microplate will become accreted after it has formed.

Figure 3 shows the model for a ridge-fault-fault geometry, which we choose for brevity and simplicity. The same concept works equally well for any triple junction that involves at least one spreading center. It is important to note that in some settings kinematics dictate that at least one of the rifts must "propagate" toward the triple junction over time (e.g., a ridge-ridge-ridge triple junction; Patriat and Courtillot, 1984), whereas in our example, rift propagation occurs from within a transform fault (Bird and Naar, 1994) near a stable ridge-fault-fault triple junction (Fig. 3, at time t_1). Rift propagation leads to microplate formation (Fig. 3, t_2), and in this model, propagation can occur into any of the three plates (and need not be into the same plate every time a new microplate forms). The microplate is active for a few million years (Fig. 3, t_3) and then attaches to one of the three plates; the southern plate in this example (Fig. 3, t_{4a}). Attachment occurs when the southern transform fault "freezes." After this transform fault is abandoned, the spreading

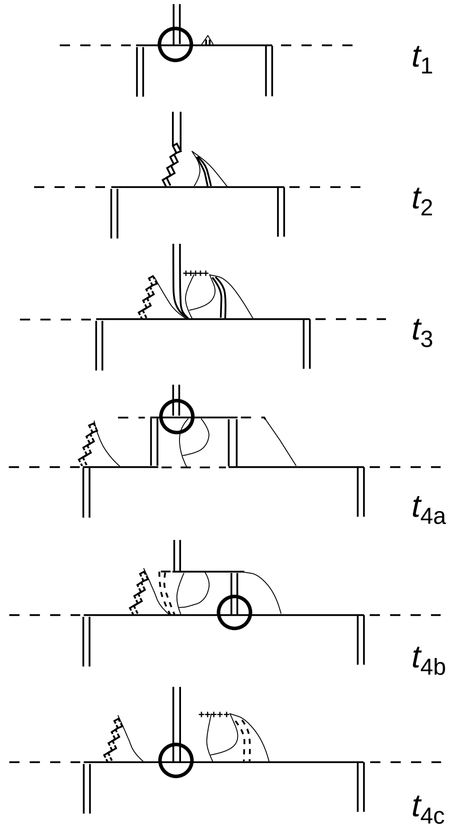

Figure 3. Episodic triple-junction migration model. Panels t_1 through t_3 show one possible evolutionary sequence of proposed model. Circle represents main triple junction between three larger plates. There are no circles in panels t_2 and t_3 because of active microplate. Double lines are spreading centers, solid horizontal lines are transform faults, dashed horizontal lines are fracture zones, dashed double lines are failed (inactive) spreading centers, other thin lines are pseudofaults, and plus signs represent compressional boundaries. Panels t_{4a} through t_{4c} show three possible outcomes after rift propagation has formed active microplate (see text).

boundaries to either side of it remain active and thus a failed rift is not formed (as is commonly found at other paleomicroplates; e.g., Mammerickx et al., 1988). In this example, the triple junction has migrated northward in a discrete jump that involved rift propagation and microplate formation. Repeated jumps of this type are what we call episodic triple-junction migration. However, if the western rift fails, then a northern transform fault would develop, and the triple junction would jump to the east (Fig. 3, t_{4b}). If the eastern rift (the propagator) fails, then the triple junction would not relocate (Fig. 3, t_{4c}). The latter two possibilities have not been documented, but we consider them likely possibilities over geologic time.

MODEL IMPLICATIONS

The model has several implications for the kind of tectonic patterns that should be produced by open-ocean triple junctions in general. First and foremost, kinematic stability of triple junctions has a limited usefulness in regard to long-term triple-junction evolution. Processes such as changing plate motions, rift propagation, microplate formation, lithospheric transfer, and microplate abandonment appear to play equally important roles in the migration history.

Second, anomalous tectonic structures can be left along the triple-junction trace, depending on how the microplates develop and then become inactive. These structures include reoriented abyssal-hill fault patterns, pseudofaults, abandoned transform faults, zones of convergence and thickened lithosphere, zones of extension and thinned lithosphere, other types of lithospheric deformation, and failed rifts, or if the microplate rift never fails, rate-change boundaries marking the time that the microplate became attached to one of the three larger plates. These rate-change boundaries are located where the failed rift would have been produced and form only in special circumstances, as described here for the evolution of the Pacific-Antarctic-Nazca triple junction (Fig. 3, t_{4a}). In locations where the spreading-rate change is significant, a change from rough to smooth abyssal-hill fabric would be expected (Menard, 1967).

This episodic triple-junction migration model may also explain how old fracture zones reactivate and how new transform faults may form. The former has occurred with the reactivation of the Chile fracture zone at the Friday microplate northern boundary and at the new southwestern boundary of the Juan Fernandez microplate. A new transform fault may form along the Juan Fernandez microplate's northern boundary should the Pacific-Antarctic-Nazca triple junction complete another episode of northward migration.

ACKNOWLEDGMENTS

Bird initiated this work at the Geological Survey of Canada. Support was provided by the Australian Research Council (Bird), the University of South Florida President and Research Councils (Tebbens and Naar), the Vanderbilt University Research Council (Kleinrock), and a 1997 Oak Ridge Associated Universities Junior Faculty Enhancement Award (Tebbens). Naar acknowledges previous support from the American Chemical Society/Petroleum Research Fund (24362-G2). We thank V. Cronin and R. Hey for constructive comments, and C. Edmisten for drafting assistance. Tectonics Special Research Centre contribution 59.

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Manuscript received December 29, 1998
Revised manuscript received June 14, 1999
Manuscript accepted July 14, 1999