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Plate motions and crustal deformation

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Introduction

Over the past 30 years, the plate tectonic paradigm has revolutionized the earth sciences through its powerful yet elegant quantitative treatment of large-scale crustal deformation, and through its conceptually integrative role within the earth sciences. This review summarizes several important developments in plate tectonic research for the period 1991 to early 1994, with emphasis placed on publications that have either significantly improved our understanding of plate motions and their relation to crustal deformation or have raised significant new questions. Revisions to the geomagnetic reversal time scale, Cenozoic plate motions, microplate kinematics, oblique convergence and deformation of forearcs, and kinematic information derived from detailed bathymetric and side-scan sonar studies are featured.

Revisions to the Geomagnetic Reversal Time Scale

Recent determinations of geomagnetic reversal ages using two independent dating techniques have led investigators to the same unexpected conclusion – many of the geomagnetic reversal ages estimated over the past three decades with potassium-argon (K-Ar) radiometric analysis are too young by up to 10%. The identification of this systematic error is important because an accurate and precise geomagnetic reversal time scale (GRTS) is essential for kinematic studies concerning variations in plate velocities and the surficial and mantle processes that control plate dynamics.

The first evidence that geomagnetic reversals younger than 5.3 Myr might be significantly older than suggested by K-Ar radiometric dating came from reversal ages estimated from marine-derived sediments exposed in southern Italy and deep-sea drilling cores [*Shackleton et al.*, 1990; *Hilgen*, 1991]. These marine sequences contain high resolution records of $\delta^{18}O$ oxygen isotope concentrations and $CaC0_3$ content, both of which depend strongly on variations in insolation (solar radiation per unit area) that are driven by variations in the earth's orbit. Such variations can be accurately predicted by orbital models that incorporate changes in precession, obliquity, and eccentricity, each of which varies with well-known periods. The inter-modulation of these three orbital parameters yields a distinctive time series of insolation (and derivative quantities such as ice volume) that can be compared to the depth records of $\delta^{18}O$ and $CaC0_3$ in order to convert stratigraphic depth to stratigraphic age. The resultant chronostratigraphies permit dating of magnetic reversals within the stratigraphic column.

Reversal ages determined with the relatively new $^{40}Ar/^{39}Ar$ radiometric dating technique [e.g. *Baksi et al.*, 1992; *Spell and McDougall*, 1992] strongly corroborate reversal ages determined via the astrochronologic techniques used by *Shackleton et al.* [1990] and *Hilgen* [1991]. The $^{40}Ar/^{39}Ar$ technique can be used to determine whether a mineral has suffered loss or addition of argon gas after it has crystallized, thereby overcoming an important source of systematic error in K-Ar dating, namely, that undetected diffusional loss or gain of argon isotopes will lead to a biased radiometric age. The close agreement between the astrochronologic and $^{40}Ar/^{39}Ar$ reversal ages, and their mutual disagreement with reversal ages estimated from K-Ar age dating indicates that an important source of systematic error in the GRTS has been discovered.

Efforts to minimize or eliminate errors in the GRTS caused by the use of reversal ages estimated from K-Ar age dating are already underway. *Cande and Kent* [1992] have derived ages for all Cenozoic and Late Cretaceous field reversals by fixing the ages for several key reversals to values given by reliable radiometric or biostratigraphic studies, and by further requiring that other reversal ages yield smoothly varying spreading rates along the southern Mid-Atlantic Ridge. Their work has sparked recent efforts to determine how the GRTS changes if the assumption of smoothly varying spreading between Africa and South America is relaxed or modified [*Baksi*, 1993; *Huestis and Acton*, 1993].

To test whether or not the astronomically-based GRTS minimizes improbable large fluctuations in spreading rates over geologically brief intervals, *Wilson* [1993*a*] determined the post-5.3 Myr spreading histories of five spreading centers in the eastern Pacific and southern Atlantic. He found that seafloor spreading rates derived for four of the five spreading centers varied significantly less over the past 5.3 Myr if astronomically-derived reversal ages were used rather than ages derived from previous versions of the GRTS. Wilson's results suggest that errors in the astronomically-calibrated reversal ages are no greater than 20,000 years, allowing previous versions of the GRTS to be excluded with high confidence.

As a consequence of the well-documented need for revisions to the GRTS, the widely used NUVEL-1 model of 3.0 Myr-average global plate velocities [*DeMets et al.*, 1990] has been recalibrated and renamed NUVEL-1A [*DeMets et al.*, 1994]. NUVEL-1A has angular velocities 4.38% slower than NUVEL-1, as well as decreased model covariances. The required decrease in global plate velocities nearly eliminates [*Gordon*, 1993; *Baksi*, 1994] a persistent ~4% difference between plate velocities predicted by NUVEL-1 and 148 geodesic rates determined from satellite laser ranging (SLR) or very long baseline interferometric (VLBI) measurements at 20 sites on five plates [*Smith et al.*, 1992]. Geodesic rates predicted by NUVEL-1A agree remarkably well with observed geodesic rates (Fig. 1), even though the latter are based on a decade or less of measurements.

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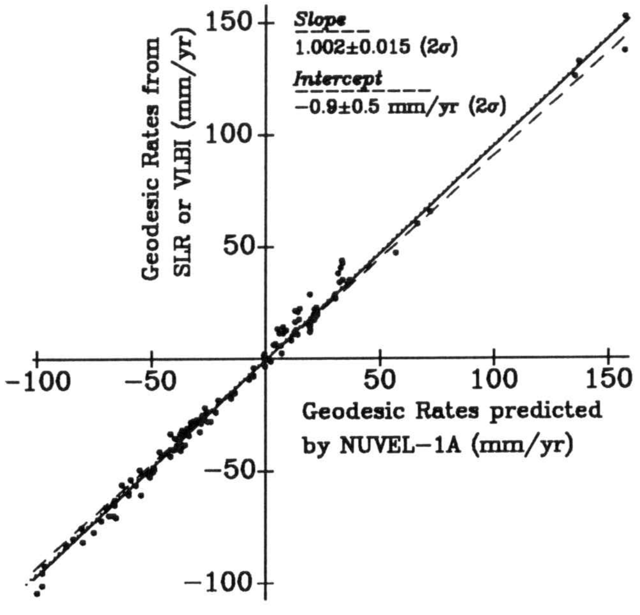

Figure 1. Non-rigorous comparison of 148 geodesic rates derived from SLR or VLBI measurements at 20 sites on five plates (Australia, Eurasia, Nazca, North America, and Pacific) [*Smith et al.*, 1992] and geodesic rates predicted by NUVEL-1A. The solid line represents the slope and intercept of the best, least-squares fit to the two sets of rates weighted by their uncertainties. Dotted line has a slope of 1.0 and intercept of 0.0, corresponding to perfect agreement between the two sets of rates. Dashed line shows the geodesic rates predicted by NUVEL-1, which are 4.38% faster than rates predicted by NUVEL-1A. A rigorous comparison of the observed and predicted geodesic rates would incorporate the variances and covariances for both sets of rates. The non-zero intercept, which implies an absolute offset of ~1 millimeter per year between the observed and predicted rates, may reflect the still limited number of plates and sites sampled by SLR or VLBI.

Cenozoic Plate Motions

Some of the most important unanswered questions about Cenozoic plate motions concern the magnitude and timing of deformation within Antarctica and other plates in the southern ocean basins, and their effects on plate circuits used to reconstruct Cenozoic plate positions. *Acton and Gordon* [1994] examine whether published plate reconstructions for the period ~70-20 Myr can bring paleomagnetic poles of similar ages but from different plates into coincidence after they are rotated into a common reference frame. They find that paleomagnetic poles from sites located on plates other than the Pacific, when rotated into a fixed Pacific reference frame via a circuit that incorporates plate boundaries surrounding Antarctica, differ significantly from coeval paleomagnetic poles determined from sites on the Pacific plate. They suggest that a systematic error within the global plate circuit, possibly as a result of deformation within Antarctica or the southern Pacific, is the most likely of several alternative explanations for the angular discrepancy between fixed Pacific and rotated non-Pacific paleomagnetic poles. New marine geophysical data from the southern Pacific and Antarctic margins however suggest that any internal deformation of the Antarctic plate probably occurred earlier than Chron 27 (~64 Myr), although a full description of this work has not yet been published [*Cande et al.*, 1992; *Raymond et al.*, 1993].

Two studies of Indian, Australian, and Eurasian plate motions have provided useful information related to the Himalayan mountain belt and initiation of distributed deformation within the seafloor south of India. Using paleomagnetic observations derived from Ocean Drilling Project (ODP) Sites 756-758 along the Ninetyeast Ridge, *Klootwijk et al.* [1991] conclude that India's rapid northward motion of 180-195 mm yr^{-1} prior to 55 Myr slowed dramatically to 45 mm yr^{-1} after ~55 Myr, and possibly again at 17 Myr. They interpret the decrease at 55 Myr as evidence for completion of the suture between India and Asia. The possible decrease at 17 Myr coincides roughly with rapid denudation and possibly, enhanced uplift of the Himalayas after 20 Myr [*Harrison et al.*, 1992]. Results reported in *Royer and Chang* [1991] raise the intriguing possibility that the initiation of deformation across a wide equatorial zone south of India may coincide with the latter event. Royer and Chang demonstrate that magnetic anomaly and fracture zone crossings from the Indian, Africa, Australian and Antarctic plates require that motion between India and Australia across their oceanic boundary south of India pre-dates Chron 5 (~11 Myr), implying that a prominent ~7-8 Ma unconformity present in drill cores from ODP Leg 116 in the central Indian basin [*Stow et al.*, 1989] does not mark the onset of regional-scale deformation related to India-Australia motion.

Roller-Bearings and Dizzy Microplates

Over the past decade, shipboard surveys of the Easter and Juan Fernandez microplates along the East Pacific Rise have revealed the complex bathymetric and magnetic seafloor fabrics that characterize the interiors and boundaries of oceanic microplates (Fig. 2). Detailed kinematic studies of both of these plates suggest that their distinctive patterns of magnetic anomalies and bathymetry result from rapid rotation of the microplates about nearby vertical axes (e.g. *Naar and Hey*, 1991; *Larson et al.*, 1992; *Rusby*, 1992). The recently proposed roller-bearing model for the kinematic evolution of oceanic microplates has drawn the various observational and kinematic studies of the Easter, Juan Fernandez, and other microplates into a promising conceptual framework [*Schouten et al.*, 1993]. In this model, a microplate behaves as a rigid or nearly rigid roller bearing whose rotation is directly proportional to its size and is caused by shear tractions imposed by the adjacent major plates (Fig. 2). The predicted rotation rate is twice that required by floating block models, in which basal shear drives the rotation. *Larson et al.* [1992] and *Schouten et al.* [1993] demonstrate that microplate rotation rates measured from magnetic anomalies created along the boundaries of the Juan Fernandez and Easter microplates agree well with those predicted by the roller-bearing model, allowing basal shear models to be excluded at a high confidence level. Whether such a model applies to rotating crustal blocks in zones of continental deformation is unknown. Unlike oceanic crust, which has numerous space-time markers (*e.g.* magnetic lineations) that record total rotations, continental block rotations must be inferred from sparse and often less precise paleomagnetic and seismologic observations. Work to date [e.g. *Jackson and Molnar*, 1990; *England and Wells*, 1991] supports basal shear models more so than edge-driven models; how-

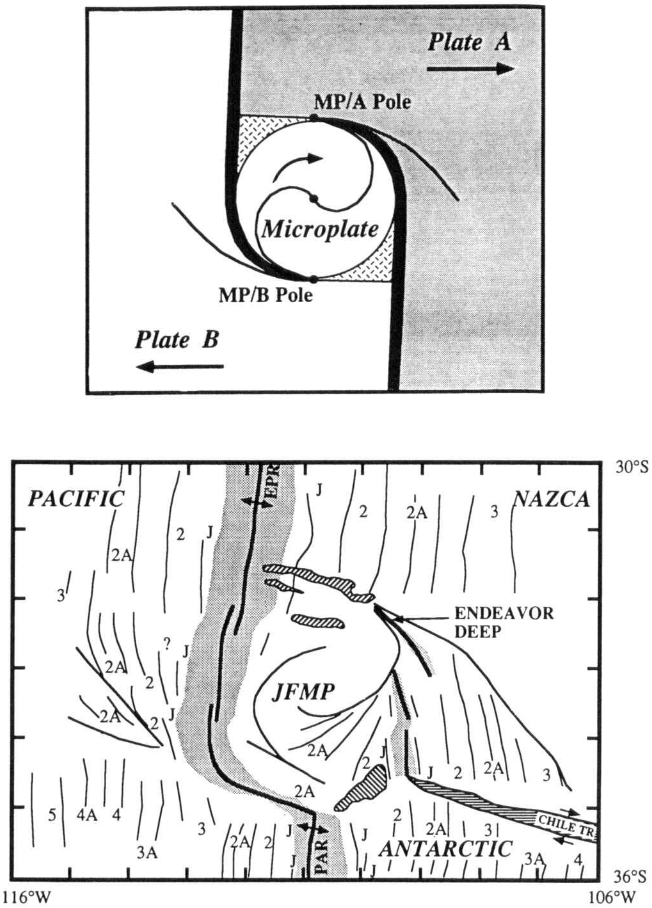

Figure 2. Upper – Microplate model based on a simple, concentrically rotating bearing. Bold dark lines show positions of major spreading centers, overlapping about the microplate. Stippled regions show areas of convergence. Lower – Magnetic isochrons and prominent faults and pseudofaults near the Juan Fernandez microplate (JFMP). Brunhes anomaly is stippled. Diagonal hatching represents compressional ridges or other complex structures. Figure and caption are modified from *Searle et al.* [1993].

ever, improved observational constraints such as high precision space geodetic measurements are essential for further progress.

Oblique Subduction

Over the past four years, studies of the kinematics and mechanics of trench-parallel translation and rotation of crustal blocks within plates that are being obliquely underthrust during subduction have demonstrated that oblique convergence is sometimes partitioned into two components, one directed more orthogonal to the local strike of a trench than the local plate convergence vector, and the other directed parallel to local strike of the trench. The former, convergent component is accommodated through subduction. The latter, margin-parallel component gives rise to shear tractions that can cause block rotations and associated extension, strike-slip motion, and shortening within the upper plate. Assuming that oblique subduction was as common in the geologic past as it is in the present, it has undoubtedly played an important role in the disassembly and reamalgamation of continental margins through translation and rotation of allochthonous (e.g. displaced) terranes.

Direct kinematic evidence for partitioning of obliquely directed convergence comes from studies of shallow-focus subduction zone earthquakes [*Jarrard,* 1986; *McCaffrey,* 1991; *DeMets,* 1992; *McCaffrey,* 1992; *Yu et al.,* 1993], which demonstrate that the horizontal slip directions from these earthquakes are commonly oriented between the direction normal to the local trace of a trench and that predicted by plate motion models such as NUVEL-1 (Fig. 3). Independent studies have demonstrated that the shear tractions imposed by the margin-parallel component of the plate vector deform the the upper plate. Geodetically-measured velocities of sites in northwestern Ecuador, located above the obliquely subducting Nazca plate, have significant trench-parallel components in the direction predicted by a simple partitioning model [*Freymueller et al.,* 1993]. *England and Wells* [1991] demonstrate that paleomagnetically determined rotations of the Columbia River Basalt group decrease exponentially as a function of distance from the Cascadia subduction zone, and suggest that the tangential component of Juan de Fuca-North America motion [*Wilson,* 1993*b*] caused the observed rotations. Seismic reflection, sidescan sonar, and bathymetric surveys of the continental shelf above the subducting Juan de Fuca plate suggest that the tangential component of motion also results in folding and clockwise rotation of fault-bounded blocks [*Goldfinger et al.,* 1992].

The factors that control partitioning of oblique convergence are also being investigated. For instance, observed convergence obliquities are not strongly correlated with the magnitude of the angular discrepancy between predicted and observed slip directions, suggesting that partitioning is determined by other factors [*McCaffrey,* 1992; *McCaffrey,* 1994]. Variability in the bulk rheological behavior of forearcs may influence partitioning – forearcs that behave elastically exhibit a lower degree of partitioning than those that behave plastically [*McCaffrey,* 1994]. *Beck* [1993] further proposes that geometrical irregularities in the trace of a subduction zone can impede or permit along-arc translation of coastal slivers due to the presence or absence of a buttress at the leading edge of such slivers.

Implications of Detailed Plate Boundary Mapping for Plate Motion Studies

The amount and quality of observational data available for kinematic studies increased dramatically during the 1980s and 1990s, due in part to the widespread use of bathymetric and side-scan sonar swath-mapping technologies for seafloor surveys. Because the vigor of research into plate motions has historically been driven by access to such data, the contributions of recent marine geophysical measurements to kinematic research are discussed here.

Multi-beam studies of spreading centers have documented the widespread occurrence of discontinuities in axial rises and valleys, ranging from several hundred meter offsets of the spreading axis (DEVALS or deviations from axial linearity) to multi-hundred km long offsets (transform faults) [*Macdonald et al.,* 1991]. Non-transform discontinuities, which occur along both slow and fast spreading centers [e.g. *Grindlay et al.,* 1992; *Carbotte and Macdonald,* 1992], often leave "wakes" analogous to pseudofaults that disrupt both the seafloor fabric and magnetic lineations flanking the ridge.

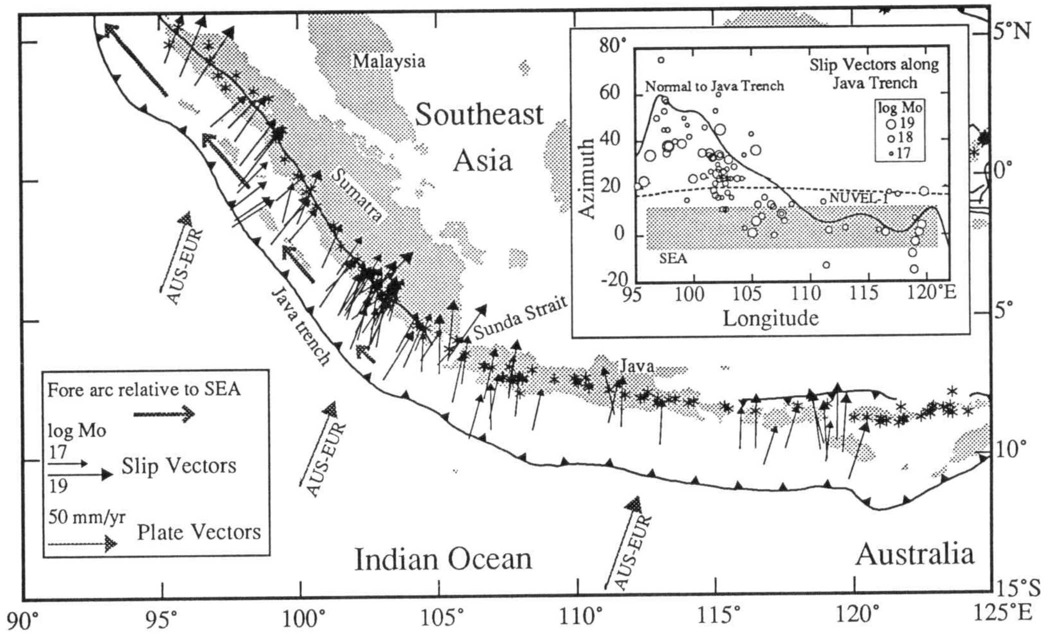

Figure 3. Java-Sumatra subduction zone, with tectonic features, earthquake slip vectors, and plate-motion vectors. Inset shows horizontal earthquake slip directions (circles), the trench-normal direction (solid line), and azimuths predicted by the NUVEL-1 Australia-Eurasia angular velocity. Note how the earthquake slip vectors parallel the trench-normal direction rather than the predicted convergence direction. Figure is modified from *McCaffrey* [1991].

Wilson [1993*b*] and *Weiland et al.* [1993] demonstrate that if dense, well-navigated kinematic data are used to solve for recent plate motions, seafloor deformations as small as a few km (such as that observed in the seafloor fabric near overlapping rift tips) can be detected. If this level of resolution can be extended to time intervals longer than a few Myr, plate reconstructions could become a powerful tool for studying the intraplate rigidity of oceanic lithosphere over long time intervals.

Recent work (e.g. *Lonsdale* [1994]) demonstrates that rapid reorientation (e.g. $<10^6$ years) of spreading axes and transform faults occurs in response to changes in plate directions. The nearly continuous record of Mesozoic and Cenozoic spreading directions recorded in seafloor created at ridges has gone largely unexploited due to the lack of modern seafloor surveys located remote from spreading centers. Fortunately, an increasing number of swath-mapping surveys are now venturing away from the ridge, and early results are promising. *Lonsdale* [1991] demonstrates that isolated swath-mapping profiles constrain the complex kinematic histories of oceanic microplates off Peninsular California, and a multibeam survey of the Pitman fracture zone between the Campbell Plateau and continental rise of Marie Byrd Land is yielding important information about the Cenozoic history of Pacific-Antarctic motion [*Cande et al.*, 1992]. The amount of useful kinematic information from the latter survey argues for similarly designed surveys along other fracture zones.

Other Topics

Other important research that has been published over the past quadrennium, but cannot be discussed due to space constraints includes the ongoing debate regarding the pre-Pangaean configuration of continents [*Dalziel,* 1992], statistically rigorous descriptions of plate motions [*Richardson and Cole,* 1991], and efforts to deduce the connections between horizontal plate motions, continental uplift, and paleoclimate [*Molnar et al.*, 1993].

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References

Acton, G. D., and R. G. Gordon, Paleomagnetic tests of Pacific plate reconstructions and implications for motion between hotspots, *Science, 263,* 1246–1254, 1994.

Baksi, A. K., A geomagnetic polarity time scale for the period 0–17 Ma, based on ^{40}Ar/^{39}Ar plateau ages for selected field reversals, *Geophys. Res. Lett., 20,* 1607–1610, 1993.

Baksi, A. K., Concordant sea-floor spreading rates obtained from geochronology, astrochronology, and space geodesy, *Geophys. Res. Lett., 21,* 133–136, 1994.

Baksi, A. K., V. Hsu, M. O. McWilliams, and E. Farrar, ^{40}Ar/^{39}Ar dating of the Brunhes-Matuyama geomagnetic field reversal, *Science, 256,* 356–357, 1992.

Beck, M. E., On the nature of buttressing in margin-parallel strike-slip fault systems, *Geology, 21,* 755–758, 1993.

Cande, S. C., and D. V. Kent, A new geomagnetic polarity time scale for the Late Cretaceous and Cenozoic, *J. Geophys. Res., 97,* 13,917–13,951, 1992.

Cande, S. C., J. Stock, C. A. Raymond, and W. F. Haxby, Changes in Pacific-Antarctic plate motion and the age of the bend in the Hawaii-Emperor chain (abstract), *Eos Trans. AGU, 73,* 507–508, 1992.

Carbotte, S., and K. Macdonald, East Pacific Rise 8°–10°30'N: Evolution of ridge segments and discontinuities from SeaMARC II and three-dimensional magnetic studies, *J. Geophys. Res., 97,* 6959–6982, 1992.

Dalziel, I. W. D., Antarctica: A tale of two supercontinents, *Annual Review of Earth and Planetary Sciences, 20,* 501–525, 1992.

DeMets, C., R. G. Gordon, D. F. Argus, and S. Stein, Current plate motions, *Geophys. J. Int., 101,* 425–478, 1990.

DeMets, C., Oblique convergence and deformation along the Kuril and Japan trenches, *J. Geophys. Res., 97,* 17,615–17626, 1992.

DeMets, C., R. G. Gordon, D. F. Argus, and S. Stein, Effect of recent revisions to the geomagnetic reversal time scale on estimates of current plate motions, *Geophys. Res. Lett.*, *21*, 2191–2194, 1994.

England, P., and R. E. Wells, Neogene rotations and quasicontinuous deformation of the Pacific Northwest continental margin, *Geology*, *19*, 978–981, 1991.

Freymueller, J. T., J. N. Kellogg, and V. Vega, Plate motions in the North Andean region, *J. Geophys. Res.*, *98*, 21,853–21,863, 1993.

Goldfinger, C., L. D. Kulm, R. S. Yeats, B. Appelgate, M. E. MacKay, and G. F. Moore, Transverse structural trends along the Oregon convergent margin: Implications for Cascadia earthquake potential and crustal rotations, *Geology*, *20*, 141–144, 1992.

Gordon, R. G., Plate tectonics: orbital dates and steady rates, *Nature*, *364*, 760–761, 1993.

Grindlay, N. R., P. J. Fox, and P. R. Vogt, Morphology and tectonics of the Mid-Atlantic ridge (25°-27°30'S) from Sea Beam and magnetic data, *J. Geophys. Res.*, *97*, 6983–7010, 1992.

Harrison, T. M., P. Copeland, W. S. F. Kidd, and A. Yin, Raising Tibet, *Science*, *255*, 1663–1670, 1992.

Hilgen, F. J., Extension of the astronomically calibrated (polarity) time scale to the Miocene/Pliocene boundary, *Earth Planet. Sci. Lett.*, *107*, 349–366, 1991.

Huestis, S. P., and G. D. Acton, A new geomagnetic polarity time scale using mutual smoothness constraints on rates from multiple spreading centers (abstract), *Eos Trans. AGU*, *74*, 217, 1993.

Jackson, J., and P. Molnar, Active faulting and block rotations in the western Transverse Ranges, California, *J. Geophys. Res.*, *95*, 22,073–22,087, 1990.

Jarrard, R. D., Relations among subduction parameters, *Rev. Geophys.*, *24*, 217–284, 1986.

Klootwijk, C. T., J. S. Gee, J. W. Peirce, and G. M. Smith, Constraints on the India-Asia convergence: Paleomagnetic results from Ninetyeast ridge, *Proc. ODP*, *121*, 777–881, 1991.

Larson, R. L., R. C. Searle, M. C. Kleinrock, H. Schouten, R. T. Bird, D. F. Naar, R. I. Rusby, E. E. Hooft, and H. Lasthiotakis, Roller-bearing tectonic evolution of the Juan Fernandez microplate, *Nature*, *356*, 571–576, 1992.

Lonsdale, P., Structural patterns of the Pacific floor offshore of Peninsular California, in *Gulf and Peninsular Provinces of the Californias, AAPG Memoir 47*, edited by J. P. Dauphin and B. R. T. Simoneit, pp. 87–125, 1991.

Lonsdale, P., Segmentation and disruption of the East Pacific Rise in the mouth of the Gulf of California, submitted to *Mar. Geophys. Res.*, 1994.

MacDonald, K. C., D. S. Scheirer, and S. M. Carbotte, Mid-ocean ridges: Discontinuities, segments, and giant cracks, *Science*, *253*, 986–994, 1991.

McCaffrey, R., Slip vectors and stretching of the Sumatran fore arc, *G*, *19*, 881–884, 1991.

McCaffrey, R., Oblique plate convergence, slip vectors, and forearc deformation, *J. Geophys. Res.*, *97*, 8905–8915, 1992.

McCaffrey, R., Global variability in subduction thrust zone-forearc systems, *Pure and Applied Geophysics*, *142*, 173–224, 1994.

Molnar, P., P. England, and J. Martinod, Mantle dynamics, uplift of the Tibetan plateau, and the Indian monsoon, *Reviews of Geophysics*, *31*, 357–396, 1993.

Naar, D. F., and R. N. Hey, Tectonic evolution of the Easter microplate, *J. Geophys. Res.*, *96*, 7961–7993, 1991.

Raymond, C. A., J. M. Stock, and S. C. Cande, Late Cretaceous - Early Tertiary plate kinematics of the south Pacific: Results of a marine geophysical survey of the Antarctic plate (abstract), *Eos Trans. AGU*, *74*, 586–587, 1993.

Richardson, R. M., and G. L. Cole, Plate reconstruction uncertainties using empirical probability density functions, *J. Geophys. Res.*, *96*, 10,391–10,400, 1991.

Royer, J.-Y., and T. Chang, Evidence for relative motions between the Indian and Australian plates during the last 20 Myr from plate tectonic reconstructions: Implications for the deformation of the Indo-Australian plate, *J. Geophys. Res.*, *96*, 11,779–11802, 1991.

Rusby, R. I., Tectonic pattern and history of the Easter microplate, based on GLORIA and other geophysical data, Ph. D thesis, Durham, England, Univ. of Durham, 1992.

Schouten, H., K. D. Klitgord, and D. G. Gallo, Edge-driven microplate kinematics, *J. Geophys. Res.*, *98*, 6689–6701, 1993.

Searle, R. C., R. T. Bird, R. I. Rusby, and D. F. Naar, The development of two oceanic microplates: Easter and Juan Fernandez microplates, East Pacific Rise, *J. Geol. Soc. London*, *150*, 965–976, 1993.

Shackleton, N. J., A. Berger, and W. R. Peltier, An alternative astronomical calibration of the lower Pleistocene timescale based on ODP Site 677, *Trans. Royal Soc. of Edinburgh: Earth Sciences*, *81*, 251–261, 1990.

Smith, D.E., J. W. Robbins, and C. Ma, Large-scale plate behavior and horizontal crustal deformation inferred from space geodetic techniques, paper presented at *International Workship on Global Positioning Systems in Geosciences*, Crete, 1992.

Spell, T. L., and I. McDougall, Revisions to the age of the Brunhes-Matuyama boundary and the Pleistocene geomagnetic polarity timescale, *Geophys. Res. Lett.*, *19*, 1181–1184, 1992.

Stow, D. A. V., J. R. Cochran, and ODP Leg 116 Scientific Party, The Bengal Fan: Some preliminary results from ODP drilling, *Geo-Marine Letters*, *9*, 1–10, 1989.

Weiland, C., D. S. Wilson, and K. C. Macdonald, High-resolution plate reconstructions of the southern Mid-Atlantic ridge, submitted to *Mar. Geophys. Res.*, 1993.

Wilson, D. S., Confirmation of the astronomical calibration of the magnetic polarity timescale from sea-floor spreading rates, *Nature*, *364*, 788–790, 1993*a*.

Wilson, D. S., Confidence intervals for motion and deformation of the Juan de Fuca plate, *J. Geophys. Res.*, *98*, 16,053–16,071, 1993*b*.

Yu, G., S. G. Wesnousky, and G. Ekström, Slip partitioning along major convergent boundaries, *Pure and Applied Geophysics*, *140*, 183–210, 1993.

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