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Notes

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ABSTRACT

Thin-viscous-sheet models have proved to be very useful in exploring the interaction between plate boundary and gravitational forces during continental collision. However, simplifications of these models (e.g., absence of faults, planar geometry of the collision zone) limit their use in making specific predictions regarding tectonic evolution, such as the role of eastward extrusion along major strike-slip faults during the Indo-Asian collision. This deficiency is overcome by a thin-shell finite-element model with faults that can assess the effects of preexisting fault configurations and topographic distributions on velocity fields. Numerical simulations of a palinspastically restored Asia at ca. 50 Ma suggest that preexisting lithospheric weaknesses favor north-south shortening during initial collision, whereas preexisting high topography in southern Asia promotes eastward extrusion. These results underscore the first-order importance of initial topography and the distribution of preexisting faults in the outcome of geodynamic modeling.

INTRODUCTION

The broad region of deformation in Asia produced by the Indo-Asian collision stands in sharp contrast to the narrow zones of deformation in oceanic lithosphere. This fundamental difference has inspired the development of thin-viscous-sheet models (e.g., Bird and Piper, 1980), which treat continental deformation as a continuum process and have provided considerable insight into the interaction of gravitational and plate-boundary forces during continental convergence (e.g., England and Houseman, 1986). However, the models cannot evaluate the effect of preexisting lithospheric weaknesses. Since Asia has been the locus of continuous continental collision, subduction, and fragmentation since 600 Ma (Şengör et al., 1988), the existence and distribution of reactivated sutures, rift systems, and faults may have exerted important controls on the accommodation of Indo-Asian convergence. To overcome this limitation, Kong and Bird (1995) developed a thin-shell, finite-element model that includes preexisting faults and utilizes a spherical geometry to represent continental-scale collision zones. The model simulates the current slip rates along major faults in Asia with high fidelity, but requires that (1) faults play a dominant role (~70%) compared to continuum deformation in accommodating the present convergence between India and Asia and (2) faults be extremely weak (Kong and Bird, 1996).

Because of several successive collisional events during the Mesozoic, complex and elevated topography may have existed in Asia immediately prior to onset of the Indo-Asian collision. Paleoelevation may be estimated directly from paleobotanical data sets (Gregory and Chase, 1992) or indirectly from the determination of lithospheric thickening and crustal denudation (Harrison et al., 1997). Recent investigations in the Lhasa block indicate that significant crustal shortening of between 60% and 70% occurred during the Cretaceous (Murphy et al., 1997). In contrast, little crustal thickening occurred within the Lhasa block during the Indo-Asian collision (Ratschbacher et al., 1992; TBGMR, 1992). Because the pre-Tertiary shortening is mostly south-directed thrusts along the Banggong-Nujiang suture, it may have caused crustal thickening in the southern Qiangtang block as

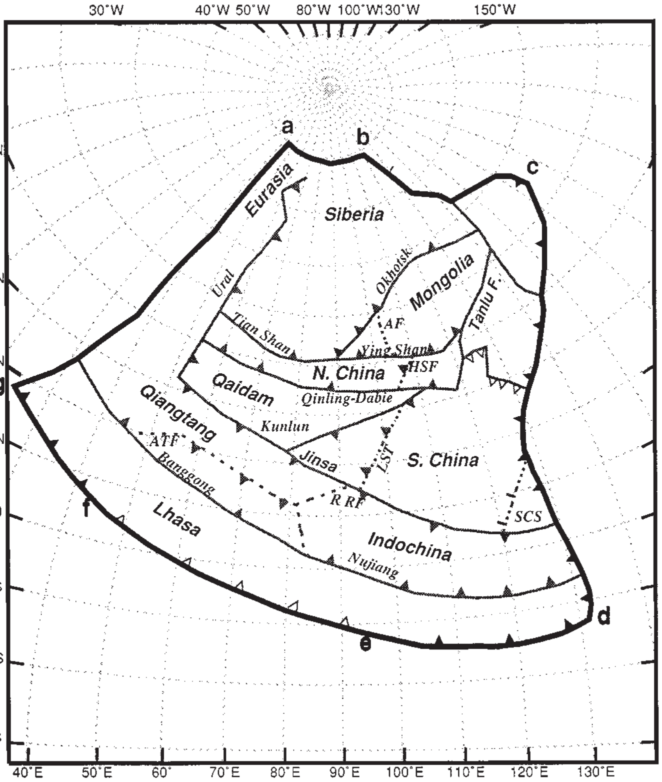

Figure 1. Tectonic reconstruction of fault configuration at onset of Indo-Asian collision at ca. 50 Ma. Dashed lines are some major late Cenozoic faults that may have been originated from reactivation of preexisting weaknesses such as sutures, faults, or failed rift systems. ATF—Altyn Tagh fault; RRF—Red River fault (possible old suture); AF—Altai fault system (possible old suture); HSF—Helan Shan fault system (possible early Paleozoic rift); LST—Longmen Shan thrust belt (possible transition zone between continental and oceanic crust); SCS—South China Sea, possibly bounded by Lisui-Haifeng suture on its west side (Yin and Nie, 1996). Names of major suture zones and continental blocks are shown.

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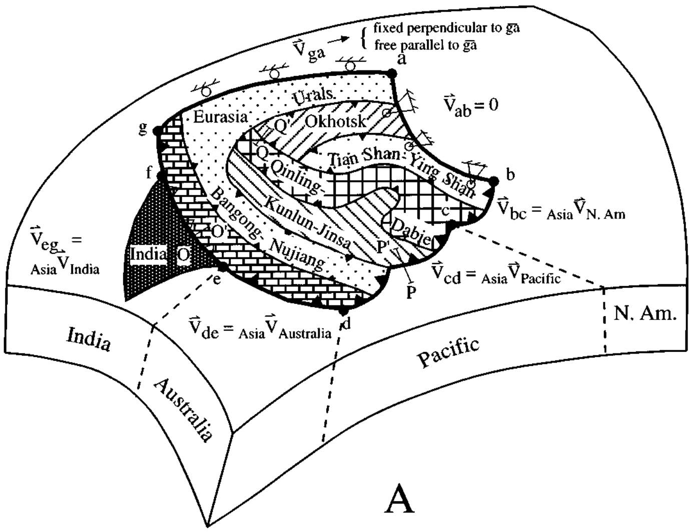

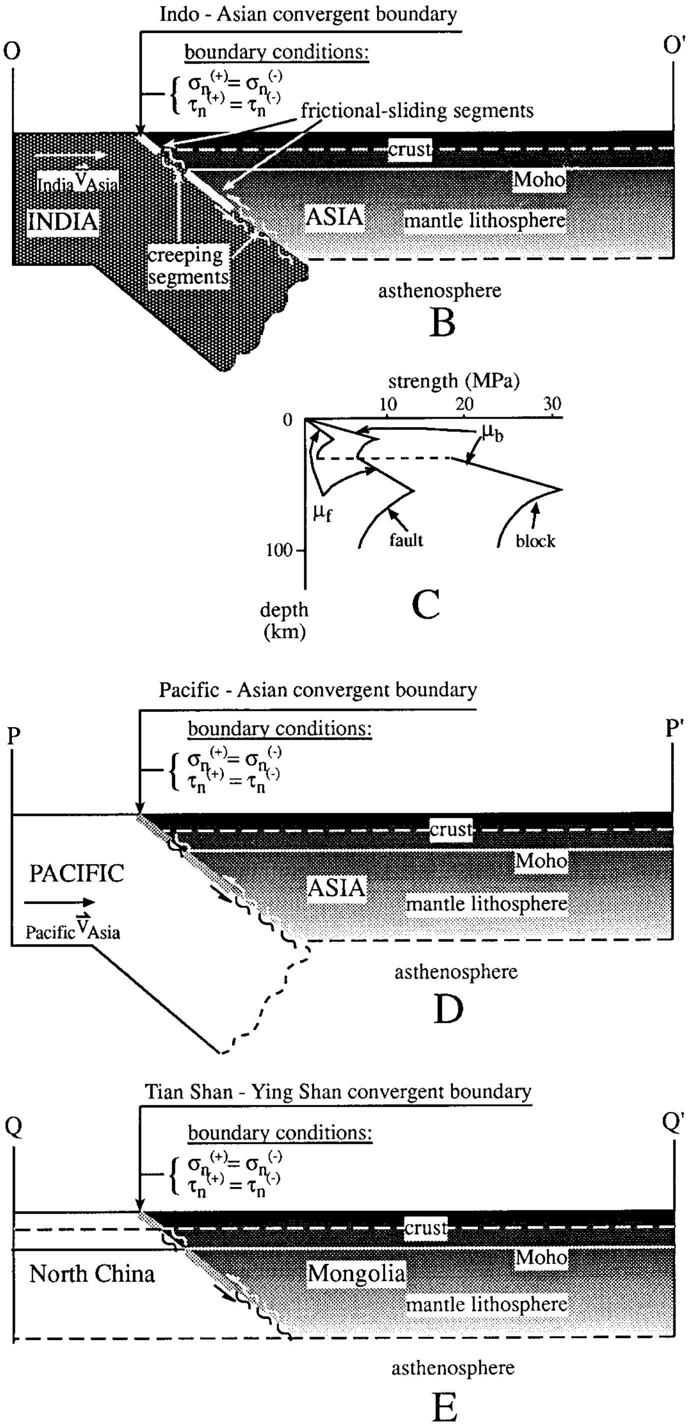

Figure 2. A: Schematic diagram showing thin-shell model and assumed boundary conditions and locations of cross sections shown in B, D, and E. B: Cross section through Indo-Asian convergent boundary. Traction continuity is assumed across the plate boundary, where σ_n is normal traction, and τ_n is shear traction. C: Vertical strength profiles for both preexisting faults and fault-bounded blocks. Note that Coulomb friction law is assumed both on faults (μ_f) and within brittle upper crust (μ_b). Dislocation creep is assumed for lower crust (i.e., quartz flow law) and lower mantle lithosphere (i.e., diabase flow law). Vertical temperature profile is calculated by one-dimensional steady-state thermal model described in Kong (1995). D: Cross section through Pacific-Asia convergent boundary. E: Cross section through Tian Shan–Yin Shan suture, a lithospheric-scale fault zone that existed prior to Indo-Asian collision. Note that crustal and lithospheric thicknesses are function of topography. Thus, they are not necessarily as uniform as shown in these schematic diagrams.

well. Assuming Airy isostasy, the estimated crustal shortening strain implies that central Tibet was raised to elevations of between 3 and 4 km during the middle Cretaceous. Sedimentological studies of the southern Asian margin suggest that central Tibet remained elevated until the Indo-Asian collision began (Dürr, 1996).

In order to evaluate the effects of preexisting fault configurations, friction along faults, preexisting topographic distributions, and traction conditions along plate boundaries on late Cenozoic deformation in Asia, we performed a series of numerical experiments on a palinspastically restored Asia at ca. 50 Ma (Yin and Nie, 1996) (Fig. 1). To explore the origin of major late Cenozoic strike-slip faults such as the Red River fault, we tested models both with and without preexisting faults.

FINITE-ELEMENT THIN-SHELL MODEL

Following Kong and Bird (1995), we approximate the lithosphere in the numerical model as a spherical thin shell with variable thickness and including faults (Fig. 2). Our model only deals with steady-state deformation. Thus, all the physical parameters used in the calculation are time independent. This allows us to focus only on the deformation of Asia at 50 Ma. We assume Coulomb friction for both the upper crust and faults, dislocation creep for the lower crust and the mantle lithosphere, a steady-state thermal regime, and Airy isostasy for determining the crustal and lithospheric thicknesses from topography. Our model uses the following boundary conditions: (1) the north side is fixed, (2) the west side is fixed perpendicular to the boundary and free to slip parallel to the boundary, and (3) the other boundaries are determined from relative plate velocities between Asia and India, Australia, and the Pacific plate at 50 Ma (Engebretson et al., 1985). We use the northwestern corner (point "a" in Fig. 2) to represent Eurasia; all velocity fields and velocity boundary conditions across plate boundaries are determined relative to this point (Figs. 3 and 4). We also assume stress continuity for both the preexisting faults and the plate boundaries (Fig. 2).

RESULTS

We have evaluated the effect of two topographic distributions within Asia at 50 Ma (1) Asia with zero elevation and (b) an elevated region within central Tibet. Our model results indicate that without elevated topography (Fig. 3A), Indo-Asian convergence is dominated by north-south shortening in southern Asia and eastward extrusion in eastern Asia. Introducing additional faults into the model not only enhances and localizes the effect of north-south shortening, but increases the magnitude of relative velocities in Asia significantly (Fig. 3B). This result suggests that rather than assisting

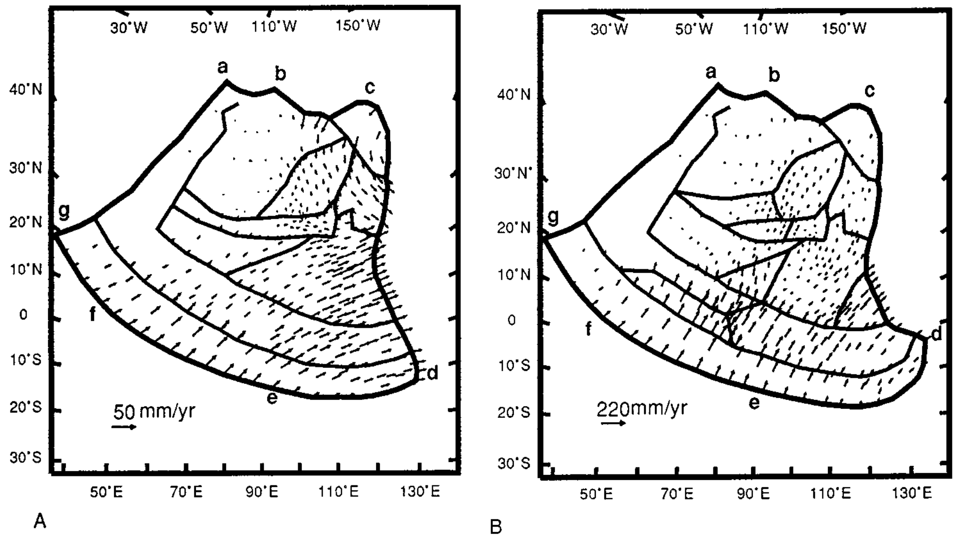

Figure 3. A: Predicted velocity field in Asia at ca. 50 Ma, assuming that Red River and other major late Cenozoic faults shown in Figure 1 did not exist at beginning of collision. We assume that effective coefficients of friction along faults and within fault-bounded blocks are 0.085 and 0.85, respectively. Shear traction is 2 MPa along eastern boundary and 25 MPa along the southern boundary. B: Predicted velocity field in Asia at ca. 50 Ma, assuming that late Cenozoic faults shown in Figure 1 originated from reactivation of preexisting weaknesses. Other conditions are same as those used in A. Note that introduction of preexisting weaknesses increases dramatically the north-south shortening in Indo-Asian collision zone.

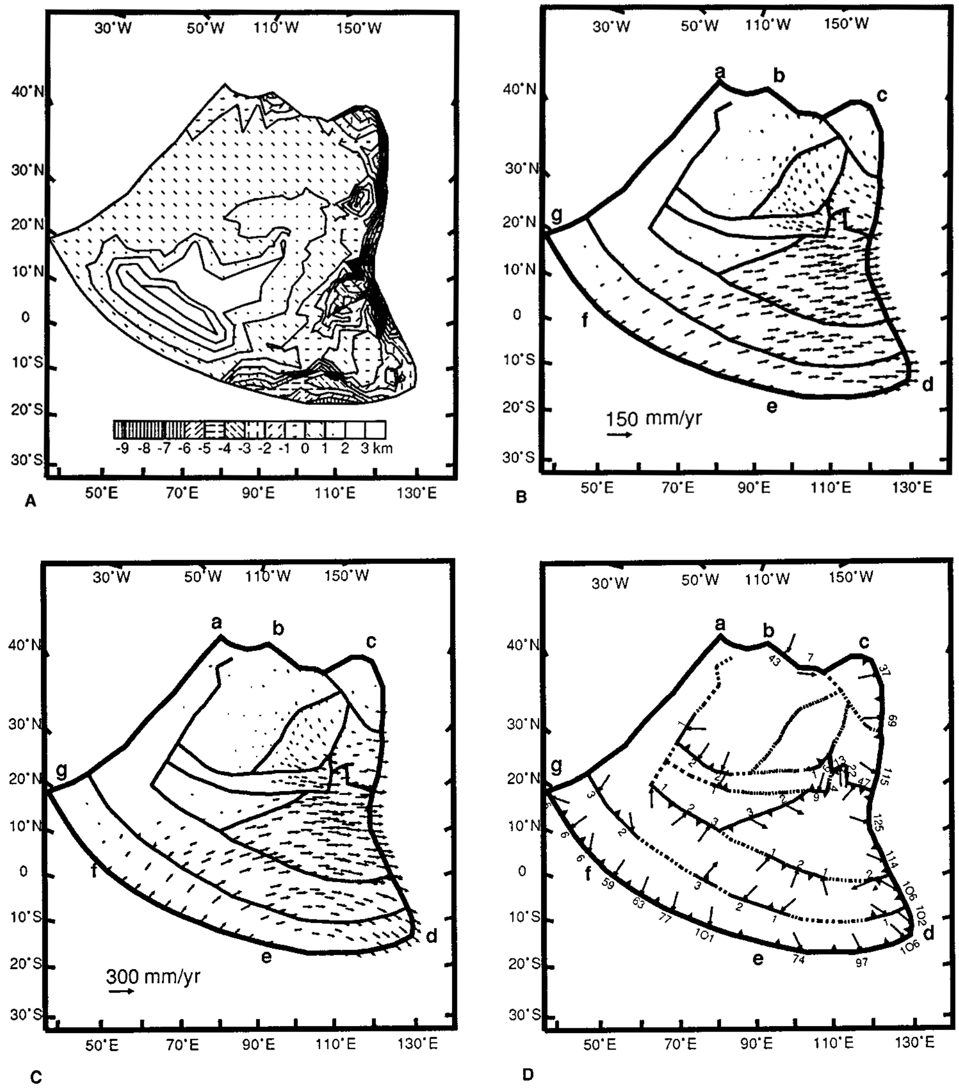

Figure 4. A: Plateau region is assigned in central Tibet with highest elevation at 4 km. We use present-day elevation of trench system in western Pacific (all below sea level with negative elevation) to simulate gravitational effect of deformation caused by topographic and thus crustal-thickness gradient in Asian continent during initial collision. Elevation of Tian Shan is assumed to be between 1 and 1.5 km. B: Velocity field for shear traction of 6 MPa along eastern margin and 17 MPa along southern margin of Asia. Effective coefficients of friction along faults and within fault-bounded blocks are assumed to be 0.085 and 0.85, respectively. Note that velocity vectors are generally parallel (i.e., translational velocity field) and point east. C: Velocity field for shear traction of 2 MPa along eastern margin and 25 MPa along southern margin of Asia. Note that southeastern Asia is dominated by strong rotational velocity field, i.e., velocity vectors show systematic clockwise rotation. D: Directions (shown by arrows) and magnitude (shown by numbers) of relative slip rates across preexisting sutures as predicted by central plateau model. Shear traction along eastern and southern boundary is 6 and 17 MPa, respectively, whereas coefficient of friction for faults and fault-bounded blocks is 0.085 and 0.85, respectively.

the eastward extrusion of continental material, the addition of faults with low frictional resistance weakens the Asian lithosphere and produces traps for localizing north-south shortening strains. Note that in both experiments, the coefficient of friction along faults is assumed to be 0.085 (ten times less than that within fault-bounded blocks), a value required in the simulation of present-day fault kinematics in Asia (Kong and Bird, 1996).

When we add a small plateau to central Tibet (Fig. 4A), the velocity field is dominated by eastward extrusion. We use a 6 MPa shear traction on the eastern boundary and a 17 MPa shear traction on the southern boundary, which are the values that best simulate the present-day fault kinematics in Asia as shown by Kong and Bird (1996) (Fig. 4B). Using a lower shear traction (2 MPa) for the east side and a higher traction (25 MPa) on the south side produces a strong rotational field in southeastern Asia (Fig. 4C), suggesting that a change from rotation (Cobbold and Davy, 1988) to eastward translation of southeastern Asia (Peltzer and Tapponnier, 1988) could be effected by a relatively subtle change in traction conditions along the plate boundaries.

Our numerical simulations showed that eastward extrusion was always promoted whether a plateau was assigned to northern, southern, or the whole of Tibet, but the resulting velocity fields were quite different from one another. A northern plateau causes very rapid east-west extension along the Kunlun suture and rapid north-south convergence along the Banggong-Nujiang suture. Both predictions are as yet unsupported by observations. Although the southern plateau model eliminates a problematic result of the northern plateau model, it favors an exceedingly high rate of thrusting in central Tibet that, again, is not supported by observation. The central-plateau model (Fig. 4D) appears to best match the geologic data: relatively fast convergence along the southern boundary between India and Asia within the Indian Tethyan sequence (Ratschbacher et al., 1994), crustal shortening at moderate rates (~1–3 mm/yr) in northern Tibet along the Jinsha and Kunlun sutures (Song and Wang, 1993), and a significant amount of eastward extrusion in the early stages of the Indo-Asian collision (Tapponnier et al., 1990; Harrison et al., 1996), as represented by the predicted velocity field (Fig. 4C).

Although not shown here, we have also explored the effect of varying the coefficient of friction along preexisting faults. When the friction along the faults and friction within the fault-bounded blocks are set to the same value (0.85), Asia is essentially rigid, and its convergence with India is almost entirely consumed along its southern boundary. This may explain the remarkably different manner in which deformation was distributed within India compared with Asia. The former has behaved like a rigid body, except in its northernmost part, whereas the latter has been pervasively deformed. The two continents had vastly different time scales available for the healing of preexisting faults. The ancient Indian craton may have lost weakening agents, such as hydrated minerals and high pore-fluid pressure in fault zones, because of fluid diffusion and exposure of high-grade (i.e., granulite facies) metamorphic terranes. In contrast, Asia as a young continent experienced numerous orogenic events since 300 Ma. Those events may have produced a high density of fault zones containing high pore-fluid pressures. When recovery intervals following orogeny are short, the maintenance of weakening mechanisms is enhanced.

CONCLUSIONS

Our results suggest that (1) an increase in the density of preexisting weakness assists north-south shortening; (2) an increase in shear traction along the eastern margin of Asia and a decrease in shear traction along the southern margin promotes eastward extrusion and simultaneously suppresses clockwise rotation in eastern Asia; and (3) a flat Asia favors north-south shortening, whereas an elevated region in south Asia promotes eastward extrusion.

As the topographic distributions and preexisting fault configurations are key initial conditions that dictate the fundamental aspects of continental deformation in a collisional system, a complete understanding of collisional processes requires the knowledge of its history during, as well as prior to, its activation. In the oceanic lithosphere, the topographic history and preexisting weaknesses can be predicted simply from plate tectonics. In notable contrast, these important parameters can only be established by site-specific geologic investigations in the continental setting.

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REFERENCES CITED

Bird, P., and Piper, K., 1980, Plane-stress finite element model of flows in southern California: Physics of Earth and Planetary Interiors, v. 21, p. 158–175.

Cobbold, P. R., and Davy, P., 1988, Indentation tectonics in nature and experiment. 2. Central Asia: Uppsala University Geological Institute Bulletin, v. 14, p. 143–162.

Dürr, S. B., 1996, Provenance of Xigaze fore-arc basin clastic rocks (Cretaceous, south Tibet): Geological Society of America Bulletin, v. 108, p. 669–684.

Engebretson, D., Cox, A., and Gordon, R. G., 1985, Relative motions between oceanic and continental plates in the Pacific basin: Geological Society of America Special Paper 206, p. 1–59.

England, P., and Houseman, G., 1986, Finite-strain calculations of continental deformation. 2. Comparison with the India-Asia collision zone: Journal of Geophysical Research, v. 91, p. 3664–3676.

Gregory, K., and Chase, C., 1992, Tectonic significance of paleobotanically estimated climate and altitude of late Eocene erosional surface, Colorado: Geology, v. 20, p. 581–585.

Harrison, T. M., Yin, A., and Ryerson, F. J., 1997, Orographic evolution of the Himalaya and Tibet, *in* Crowley, T. J., and Burke, K., eds., Tectonic boundary conditions for climate reconstructions: Oxford, Oxford University Press (in press).

Harrison, T. M., Leloup, P. H., Ryerson, F. J., Tapponnier, P., Lacassin, R., and Chen Wenji, 1996, Diachronous initiation of transtension along the Ailao Shan–Red River shear zone, Yunnan and Vietnam, *in* Yin, A., and Harrison, T. M., eds., The tectonic evolution of Asia: New York, Cambridge University Press, p. 208–226.

Kong, X., 1995, Numerical modeling of the neotectonics of Asia: A new spherical shell finite element method with faults [Ph.D thesis]: Los Angeles, University of California, 227 p.

Kong, X., and Bird, P., 1995, SHELLS: A thin-shell program for modeling neotectonics of regional or global lithosphere with faults: Journal of Geophysical Research, v. 100, p. 22129–22131.

Kong, X., and Bird, P., 1996, Neotectonics of Asia: Thin-shell finite-element models with faults, *in* Yin, A., and Harrison, T. M., eds., The tectonic evolution of Asia: New York, Cambridge University Press, p. 18–34.

Murphy, M. A., and eight others, 1997, Significant crustal shortening in south-central Tibet prior to the Indo-Asian collision: Geology (in press).

Peltzer, G., and Tapponnier, P., 1988, Formation and evolution of strike-slip faults, rifts, and basins during the India-Asia collision: An experimental approach: Journal of Geophysical Research, v. 93, p. 15095–16116.

Ratschbacher, L., Frisch, W., Chen, C., and Pan, G., 1992, Deformation and motion along the southern margin of the Lhasa block (Tibet) prior to and during the India-Asia collision: Journal of Geodynamics, v. 16, p. 21–54.

Ratschbacher, L., Frisch, W., Liu, G., and Chen, C., 1994, Distributed deformation in southern and western Tibet during and after the India-Asia collision: Journal of Geophysical Research, v. 99, p. 19917–19945.

Şengör, A. M. C., Altiner, D., Cin, A., Ustaomer, T., and Hsü, K. J., 1988, Origin and assembly of the Tethyside orogenic collage at the expense of Gondwanaland: Geological Society [London] Special Publication 37, p. 119–281.

Song, T., and Wang, X., 1993, Structural styles and stratigraphic patterns of syndepositional faults in a contractional setting: Example from Quaidam basin, northwestern China: American Association of Petroleum Geologists Bulletin, v. 77, p. 102–117.

Tapponnier, P., and eight others, 1990, The Ailao Shan–Red River metamorphic belt: Tertiary left-lateral shear between Indochina and South China: Nature, v. 343, p. 431–437.

TBGMR (Tibetan Bureau of Geology and Mineral Resources), 1992, Geologic map of Xiang Autonomous Region: Beijing, Geological Publishing House, scale 1:500 000.

Yin, A., and Nie, S., 1996, A Phanerozoic palinspastic reconstruction of China and its neighboring regions, *in* Yin, A., and Harrison, T. M., eds., The tectonic evolution of Asia: New York, Cambridge University Press, p. 442–485.

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