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Propagating extrusion tectonics in Asia: New insights from simple experiments with plasticine

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ABSTRACT

Plane indentation experiments on unilaterally confined blocks of plasticine help us to understand finite intracontinental deformation and the evolution of strike-slip faulting in eastern Asia. Several large left-lateral strike-slip faults may have been activated successively, essentially one at a time. The experiments suggest that the penetration of India into Asia has rotated (≈25°) and extruded (≈800 km) Indochina to the southeast along the then left-lateral Red River fault in the first 20 to 30 m.y. of the collision. This process can account for the opening of the South China Sea before late Miocene time. Extrusion tectonics then migrated north, activating the Altyn Tagh fault as a second major left-lateral fault and moving southern China hundreds of kilometres to the east. As this occurred, Indochina kept rotating clockwise (as much as 40°), but the sense of motion reversed on the Red River and other strike-slip faults in the south. Opening of the Mergui basin and Andaman Sea (up to the present) also appears to be a simple kinematic consequence of the extrusion. Recent rifts in northeastern China and Yunnan may be considered incipient analogs of the South China and Andaman Seas. Other Tertiary tectonic features such as the sedimentary basins of the Gulf of Thailand may be explained as collisional effects, if one uses our experiments as a guide. The experiments also suggest that a major left-lateral strike-slip fault and rift system will propagate across the Tien Shan, Mongolia, and Baikal to the Sea of Okhotsk.

INTRODUCTION

Intense and widespread seismicity in central and eastern Asia can be interpreted as a direct consequence of the collision between India and Asia (Molnar and Tapponnier, 1975). A large part of the *active deformation* of the Asian continent can be accounted for by giant strike-slip faults that "guide" the "instantaneous" tectonics and allow the extrusion of the Asian crust and lithosphere sideways, mostly to the east, in front of impinging India (Tapponnier and Molnar, 1977, 1979) (Fig. 1). The basic concept is that a "rigid" die (India) indents a "plastic" body (Asia). Plane-strain plasticity theory achieves some degree of success in predicting the instantaneous kinematics and stress field for different indenter geometries and boundary conditions thought to be grossly analogous to those of the India-Eurasia collision (Tapponnier and Molnar, 1976). However, this approach is limited by its simplicity and by drastic assumptions about the rheology of the deformable material. Moreover, earthquakes in Asia reflect only the final instant in a complex deformation process that has been in progress for at least 40 m.y. Since the initial suturing of the two continents, India, except in the north, has remained rigid (Molnar and Tapponnier, 1981) and has penetrated at least 2,000 km into Asia (Molnar and Tapponnier, 1975). It is therefore important to understand the *evolution in time* of intracontinental deformation in Asia, not only for "local" reasons but also because it is the best example we have for understanding the many continental collisions that have commanded the formation of orogenic belts in the past 2 b.y.

In order to simulate such a complex evolution, one can make numerical models (for example, Daignières and others, 1978) or, using visual markers, study experimentally the deformation of "analog" materials such as plasticine, paraffin, or clay (Cobbold, 1975; Daignières, 1975). In both cases, mostly plane-strain or plane-stress situations are easily accessible, and it has been difficult to account for the effect of body forces. This renders uncertain any quantitative comparison with the deformation of the lithosphere where crustal thickening and thinning, which are related to gravity in an essential way, can be important. Nevertheless, both approaches provide key structural and kinematic information. We have chosen to explore experimentally the India-Eurasia collision for two "geologic" reasons: (1) to study the growth, mechanism, and interaction of *faults*, as well as their influence on the displacement field, and (2) to analyze *large finite displacements and deformations*. We have built a simple but versatile indentation machine with which different materials can be deformed under different boundary conditions (Peltzer and others, 1982). We present here the first results of some experiments and discuss new insights they provide into the Tertiary tectonics of Asia.

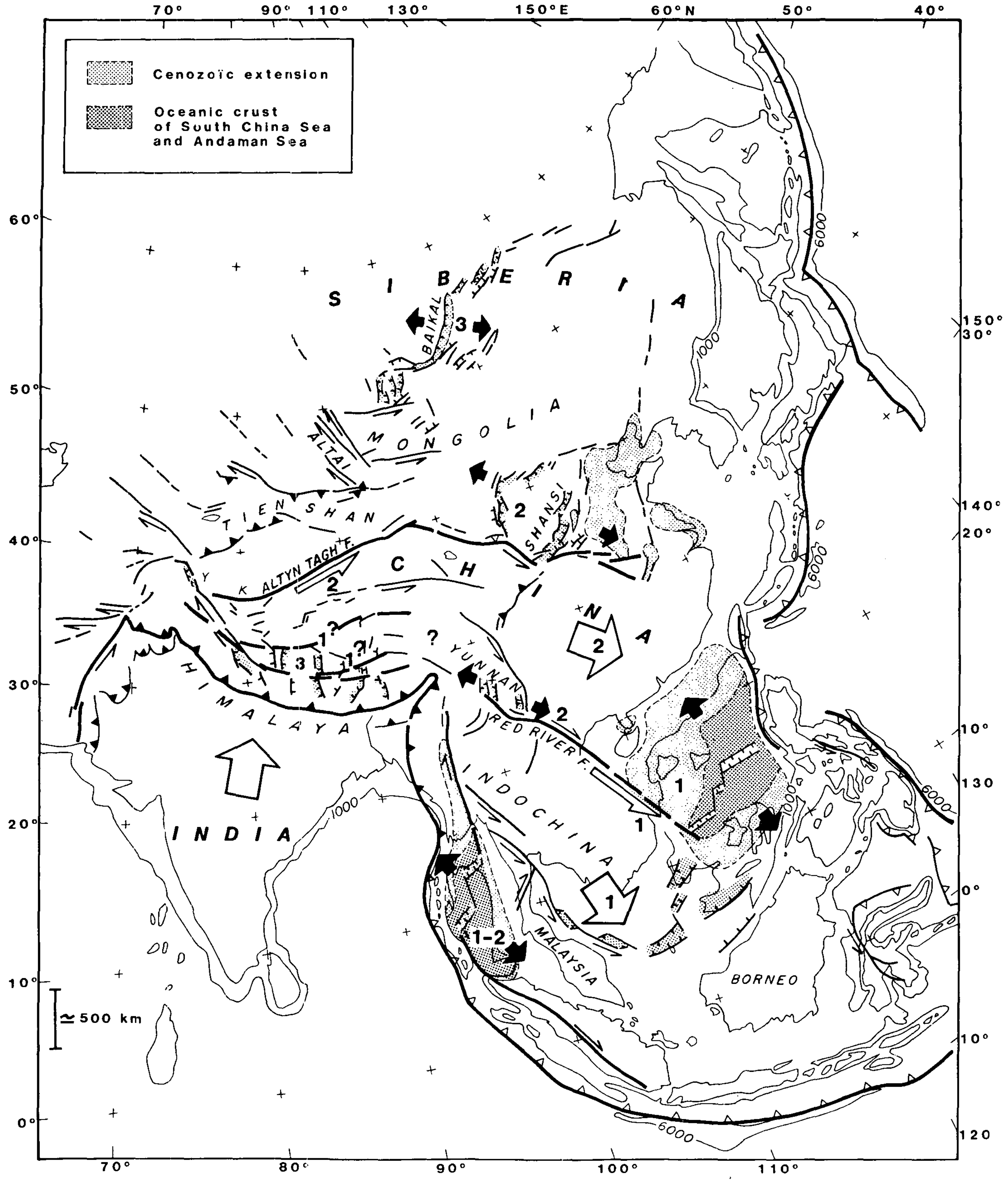

Figure 1. Schematic map of Cenozoic extrusion tectonics and large faults in eastern Asia. Heavy lines = major faults or plate boundaries; thin lines = less important faults. Open barbs indicate subduction; solid barbs indicate intracontinental thrusts. White arrows represent qualitatively major block motions with respect to Siberia (rotations are not represented). Black arrows indicate direction of extrusion-related extension. Numbers refer to extrusion phases: 1 ≃ 50 to 20 m.y. B.P.; 2 ≃ 20 to 0 m.y. B.P.; 3 = most recent and future. Arrows on faults in western Malaysia, Gulf of Thailand, and southwestern China Sea (earliest extrusion phase) do not correspond to present-day motions.

EXPERIMENTAL SETUP AND DEFORMABLE MATERIAL

A rectangular block of deformable material is placed in a transparent plastic (Perspex) box 11 cm high and 30 cm square. Plane horizontal strain is maintained by two Perspex plates, which bound the lower and upper surfaces of the block and are lubricated with talc powder. This assembly rests in a larger one, which keeps the temperature constant (25 ± 1 °C). The deformable block itself is composed of vertical layers, 5 mm thick, of homogeneous plasticine welded together with trichloroethane. By using alternating yellow and violet layers of plasticine (Cobbold, 1975), one can make accurate measurements of fault displacements and ductile strains and test the vertical invariance of the deformation. Standard Harbutt plasticine exhibits little strain hardening and closely follows the Von Mises yielding criterion. Its steady-state rheology can be described by a power-flow law of the type $\epsilon = K\sigma^n$, where $n \simeq 7.5$ at 25 °C (McClay, 1976). The yield stress is about 10^5 Pa for strain rates on the order of 10^{-7} s^{-1} (Daignières, 1975).

The indenter (5 cm wide) can be advanced at a constant rate (2.5 cm/h here) in a given direction by means of a screw-jack coupled to a stepping motor. For simple geometric and kinematic comparisons with the collision between India and Asia ($\simeq$ 5 cm/yr of convergence along a collision front of $\simeq$2,000 km), the scale factors (ratios between homologous quantities in model and natural prototype) are $K_x = 2.5 \times 10^{-8}$ for length, $K_t = 5.7 \times 10^{-12}$ for time, and $K_v = K_x \cdot K_t^{-1} = 4.4 \times 10^3$ for velocities. If gravitational and inertial forces were negligible with respect to surface forces, we would be justified in choosing two of these scale factors independently of one another.

EFFECTS OF THE FREE LATERAL BOUNDARY CONDITION IN PLANE STRAIN

The asymmetry of collisional deformations in Asia (Fig. 1) suggests that continental lithosphere in western Eurasia offers more resistance to lateral motions than do subduction zones along the Pacific and Indonesian margins (Molnar and Tapponnier, 1975; Tapponnier and Molnar, 1977, 1979). The first goal of our study was thus to test this hypothesis in the situation of a free lateral boundary. The results of this experiment (D, E, F in Figs. 2 and 3) are compared with those of a symmetrical experiment (A, B, C in Figs. 2 and 3) where the plasticine block is confined by vertical Perspex plates on both sides. In the asymmetrical experiments, the free side lies initially 5 cm away from the right tip of the indenter. Figure 2 shows three successive stages of deformation observed in the plasticine for increasing amounts of penetration of the indenter. In both experiments, the indenter displacements at each stage were about (1.2 cm (A and D), 3.5 cm (B and E), and 6.3 cm (C and F). Deformations are concentrated along narrow shear zones or faults, which appear rapidly, approximately parallel to planes of maximum shear stress (instantaneous "slip lines"). The geometry, kinematics, and evolution of these faults have a profound influence on the displacement field (Figs. 2, 3). As found in numerical solutions (Daignières and others, 1978), the influence of the free lateral boundary changes the deformation pattern in a drastic manner.

In the *bilaterally confined* experiments, the deformation fluctuates in a pattern that keeps an overall symmetry, and right-lateral and left-lateral faults play balancing roles. The triangular region in front of the indenter soon "freezes" ("dead triangle") and becomes welded to and moves along with the indenter. Hence, during most of the experiment, the largest displacements occur along the sides of this triangle (F and F′, Fig. 3, B, C). As the indenter penetrates farther into the plasticine, new faults, alternately left-lateral and right-lateral, successively form near the apex of the triangle (Fig. 2); cumulative offsets along them seldom exceed about 10 mm (Fig. 3). The faults die out a few centimetres away from the indenter.

In the *unilaterally confined* experiments, deformation quickly becomes asymmetrical; predictably, faults that allow displacements toward the free side take the leading part. In particular, the left-lateral fault that originates at the left tip of the indenter (F_1 in Fig. 3) grows and curves out to join one of the inherent discontinuities of the model (an interface between two layers of plasticine), along which it propagates to the free surface. Thereafter, it becomes predominant and guides the extrusion and rotation of a block of plasticine whose size depends on the indenter width and on the distance to the free side. Maximum offsets along this fault can reach 25 to 35 mm (over twice the maximum offsets observed along faults in the symmetrical experiment, F and F′ excepted). The extruded block rotates about 25° clockwise almost rigidly. As in the symmetrical experiment, increasing penetration of the indenter causes the deformation to migrate farther into the plasticine and to repeat itself in some ways (E in Figs. 2 and 3); a second extrusion phase develops along a second major fault (F_2) which allows large displacements to the right and clockwise rotation of a second block, analogous in size to the first one (E in Figs. 2 and 3). Faults active during the first extrusion phase essentially stop, and some (notably the left segment of F_1) are deformed during the second phase. The rotation of the first block continues to a maximum of 40° (F in Figs. 2 and 3).

In unilaterally confined experiments, there exists no steady-state dead triangle (D, E, F in Figs. 2 and 3). Thus, the left extremities of F_1 and F_2 migrate and bend progressively against the front edge of the indenter. Numerous gaps, akin to pull-aparts along strike-slip faults in the earth, open along the left-lateral faults to the right (E, F in Figs. 2 and 3). The largest ones form along F_1 and F_2, near the free edge. F_1 terminates into a particularly spectacular wedge-shaped gap (E and F in Fig. 3) whose opening results from the rotation of the first extruded block. The kinematics of the experiment require the progressive widening of another wedge-shaped gap between the right side of the indenter and the extruded plasticine (E, F in Figs. 2 and 3).

TERTIARY TECTONIC EVOLUTION OF CENTRAL AND EASTERN ASIA

Interpretations of natural tectonic situations with the help of model experiments must be done with great caution. Plane horizontal strain experiments focus attention on strike-slip faulting to the exclusion of equally important tectonic processes such as thrust faulting (Tapponnier and Molnar, 1976). The influence of anisotropic layering on the deformation of plasticine is not easy to assess. More important, it is still difficult to scale material properties, partly because of our ignorance of the long-term average mechanical behavior of the continental crust and lithosphere. If one merely looks at geometric and kinematic aspects, however, the resemblance between Figure 1 and Figure 3F (Peltzer and others, 1982) warrants attention.

First, whereas left-lateral offsets along the large strike-slip faults of central China may reach several hundred kilometres (Tapponnier and Molnar, 1977), right-lateral offsets along the smaller strike-slip faults of the Tien Shan and Altai do not exceed tens of kilometres (Tapponnier and Molnar, 1979) (Fig. 1). Orders of magnitude of offsets on corresponding faults in

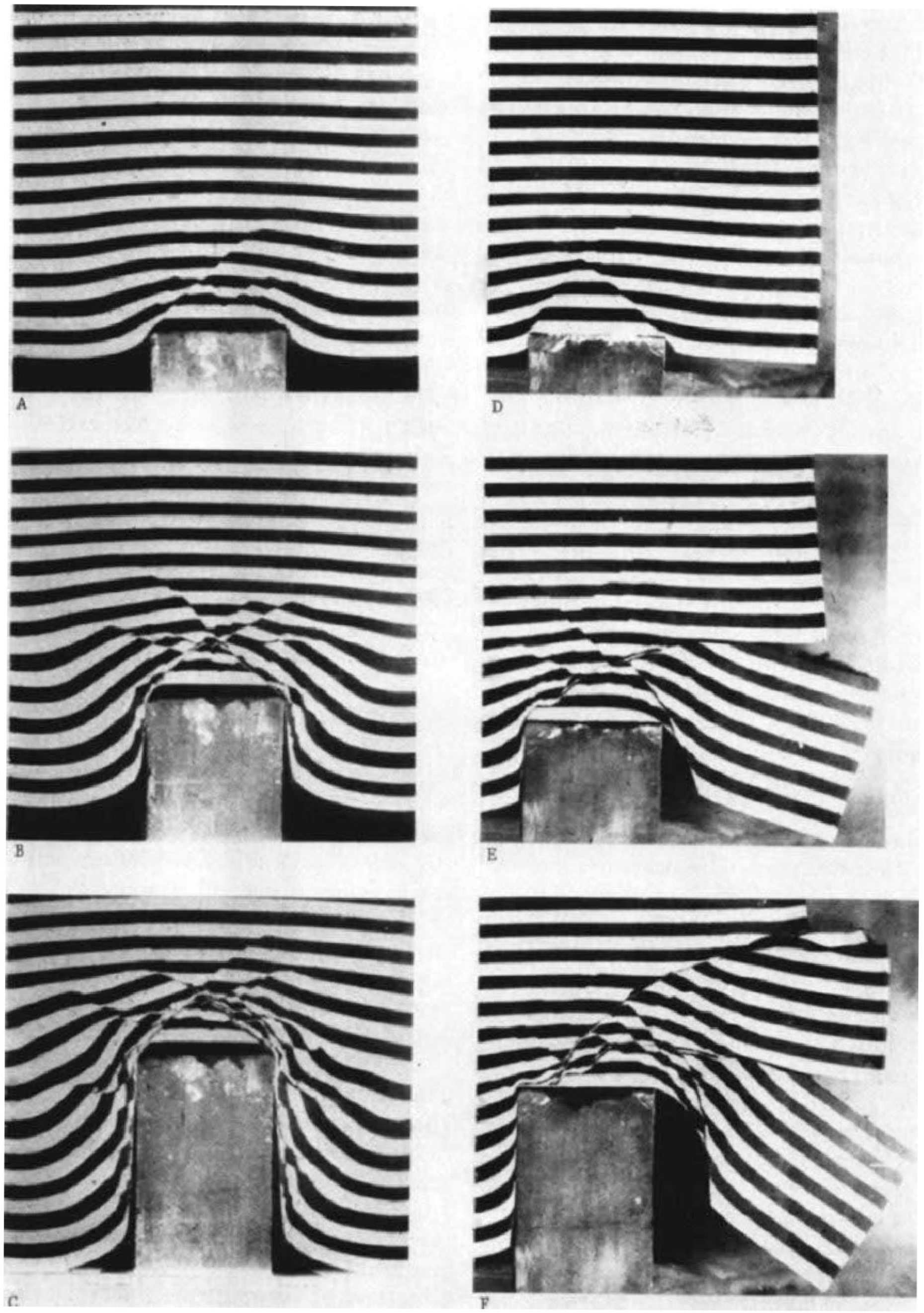

Figure 2. Three successive stages of two indentation experiments on plasticine. A, B, C: bilaterally confined; D, E, F: unilaterally confined (free side on right). Indenter displacements for A and D = 1.2 cm; for B and E = 3.5 cm; for C and F = 6.3 cm. Note narrow shear zones or faults, and open gaps on right side in E and F (after Peltzer and others, 1982).

the unilaterally confined experiments are comparable (10 mm in the experiment are equivalent to 400 km in Asia) (E, F in Fig. 3). Second, the gaps that form along the left-lateral faults in the unilaterally confined experiment reflect an extensional character of the deformation, absent in the bilaterally confined experiment, and thus essentially are related to the existence of the free boundary (E, F in Figs. 2 and 3). Although their shapes are influenced by the layering of the plasticine, the gaps are analogous to the rifts and extensional basins of northeast China (Shansi), Mongolia, and Siberia (Baikal), whose formation, in this part of northern Asia *only*, can be viewed as a direct consequence of the small resistance to eastward extrusion opposed by subduction zones along the Pacific margin of Asia (Tapponnier and Molnar, 1977, 1979). The experiments, therefore, support the idea of a drastic asymmetry in the geodynamic boundary conditions in Asia.

More interesting are new inferences that can be drawn from the experiments. *One* left-lateral strike-slip fault, the Altyn Tagh–Gansu–Wei He fault, is predominant in the recent deformation of Asia (Fig. 1). It is at least 2,500 km long (Tapponnier and Molnar, 1977), and its Tertiary offset may reach 500 to 700 km in the west, where the Permian-Triassic margin of Laurasia appears to have been sheared and displaced by that amount (Academia Sinica, 1971; Tapponnier and others, 1981). This can be accounted for if one identifies the fault with one of the major faults (F_1 or F_2) emanating from the left tip of the indenter (E, F in Fig. 3). The clockwise bending and flattening of the western extremity of the Altyn Tagh fault "against" the Karakorum range south of Khotan and Yarkand (K, Y in Fig. 1) (Academia Sinica, 1971) can be compared to the deformation of the left extremities of F_1 or F_2 against the front edge of the indenter in the experiment (E, F in Fig. 3).

The most important implications of these experiments concern the evolution and northward migration of large-scale strike-slip faulting in Asia. Seafloor-spreading reconstructions allow 2,500 to 3,500 km of convergence between *northeastern India* and Asia since 40 to 50 m.y. ago (Molnar and Tapponnier, 1975). Given the uncertainties in the date of collision, and allowing for 1,000 to 1,500 km of shortening through thickening of the continental crust, the amount of convergence to be accounted for by extrusion along strike-slip faults would thus be between 1,000 and 2,500 km. If it has reached 2,000 km, comparison of present-day Asian tectonics with a stage intermediate between E and F in the unilaterally confined experiment (Figs. 2, 3) would be appropriate, and the propagating pattern of deformation which causes successive extrusion and rotation of plasticine blocks in the unilaterally confined experiment might have had an equivalent in Asia. We suggest identifying F_2 in the experiment with the *Altyn Tagh fault*, and F_1 with the *Red River fault* (Fig. 1; E, F in Fig. 3). The Tertiary tectonics of eastern Asia would thus reflect the succession in time of two major phases of continental extrusion.

In the first 20 to 30 m.y. of the collision, the northward drive of continental India into Asia would have caused the extrusion (800 to 1,000 km) to the southeast and clockwise rotation (≃25°) of most of Indochina and the Sunda shelf (Fig. 1). *Huge left-lateral movements along the Red River fault* (a reactivated Triassic suture along some of its length) would have led to the

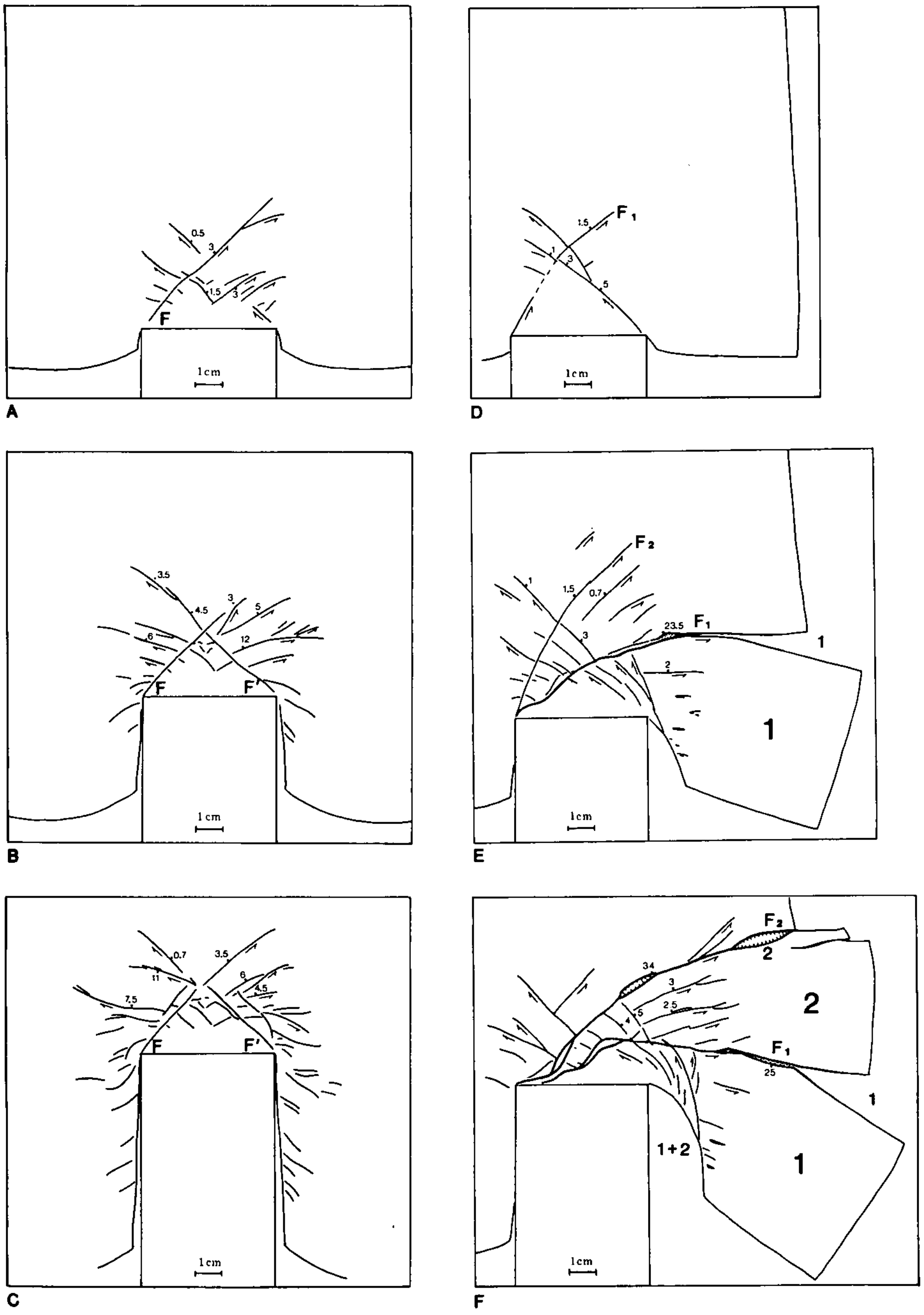

Figure 3. Hand drawings of faults observed in experiments of Figure 2, with cumulative offsets in millimetres (small numbers) (after Peltzer and others, 1982). In unilaterally confined experiment, two major faults (F1 and F2) guide successive extrusion of two blocks. In stage F, blocks 1 and 2 can be compared to Indochina and southern China, and open gaps 1, 1 + 2, and 2 to South China Sea, Andaman Sea, and northeastern China, respectively.

opening of the South China Sea from an initial rift branching off the extremity of the fault, much as the Shansi rift does now off the Altyn Tagh–Gansu–Wei He fault. The South China Sea would be analogous to the large gap at the right extremity of F_1 in the experiment. The anisotropy of the plasticine determines the orientation of this gap, but its wedge shape is a consequence of the rotation of the block extruded along F_1. Thus, one might predict more opening in the eastern part of the South China Sea. Available data on the South China Sea (Taylor and Hayes, 1980; Holloway, 1981) support this interpretation. The onset of Tertiary extension is imprecisely dated, but magnetic anomalies can be identified only between 32 and 17 m.y. B.P. There has been more seafloor spreading in the northeastern part of the sea, whose wedge shape (Fig. 1) may indicate that the spreading axis has propagated westward (Courtillot, 1980). The experiments also suggest that *cessation of spreading* in the South China Sea in the early Miocene is a consequence of northward migration of continental extrusion. As the Red River fault, slowly overtaken by India, could no longer efficiently play its extruding role, left-lateral motion on it would have come to a halt. The Altyn Tagh fault would have taken the leading role as the new left-lateral giant required for continental extrusion to proceed. Thus, 10 to 20 m.y. ago, a second phase of extrusion would have begun, moving Tibet and southern China several hundred kilometres eastward (Fig. 1), as Indichina kept rotating clockwise (as much as ≃40°). Apparently, the Altyn Tagh–Gansu–Wei He fault is still propagating eastward, inching closer to the Pacific subduction zone. Crustal extension near its eastern extremity (Shansi Rift, North China plains, Bo Hai gulf) may give birth to an ocean basin comparable to the South China Sea.

The kinematics of the unilaterally confined experiment help explain other large-scale Tertiary tectonic features in southeast Asia. We suggest that the Mergui basin, Andaman Sea, and lowlands of Burma (Fig. 1) are merely a consequence of the collision-driven extrusion and correspond to the wedge-shaped gap that *keeps opening* along the right side of the indenter *until the end of the experiment* (Figs. 2, 3). The Andaman-Mergui basin, wider in the south, narrows progressively northward into the Burmese lowlands, where huge thicknesses of Tertiary sediments probably cover oceanic crust (Mitchell and McKerrow, 1975). Extension may have started in the Oligocene in the south (Mergui basin) (Hamilton, 1979), and Miocene ocean floor is well documented in the Andaman Sea (Curray and others, 1978). In contrast to the South China Sea, *active extension,* together with right-lateral strike-slip motion along the Sagaing fault is *still in progress* in the Andaman Sea.

Complexities of the tectonics of Burma, Thailand, and Yunnan may also be accounted for in this propagating extrusion scenario. Offsets observed there on Landsat images and in the field on large conjugate strike-slip faults are not consistent with the present orientation (approximately north-south) of the maximum horizontal stress inferred from fault-plane solutions of earthquakes (A. Y. Le Dain and others, in prep.). This paradox can be solved if Indochina and Malaysia are rotated back (anticlockwise) about 40°; the early geometry and kinematics of the strike-slip faults of southern Yunnan and eastern Burma then become compatible with extrusion along the Red River fault, while those of faults in northeastern and peninsular Thailand suggest an earlier, limited, extrusion phase (Fig. 1). At the onset of collision, in a failed attempt to separate the southern part of the Sunda shelf from mainland Indochina, this phase may have shaped the Malay Peninsula, and created, as pull-aparts and rifts, the Tertiary basins of the Gulf of Thailand and the southwestern China Sea (Hamilton, 1979).

Although reversal of the sense of motion on early left-lateral faults appears to have occurred in southeast Asia, it has not been detected so far in our experiments. The most outstanding illustration is the Red River fault, now clearly right-lateral (Tapponnier and Molnar, 1977). Perhaps this is because of the more complex boundary conditions in Asia; incipient collision with Australia may now resist southeastward motion of Indonesia, or India and Indochina may now be welded by more extensive collision along the Indo-Burman ranges. In any event, right-lateral faulting on the Red River fault and rifting in Yunnan can be viewed as consequences of the present extrusion phase. Moreover, the Yunnan rifts may correspond to an incipient analog of the Andaman-Mergui basin (Fig. 1).

Eventually, continental extrusion could migrate farther north. If identified with the northern Pamirs, the northwestern tip of the Indian indenter already lies a few hundred kilometres north of the western extremity of the Altyn Tagh fault (Fig. 1). Comparisons with advanced stages of the unilaterally confined experiment suggest that if India continues its northward journey into the Asian continent, a third major left-lateral strike-slip fault system should propagate to the Sea of Okhotsk, connecting faults in the Tien Shan, Mongolia, and Baikal (Fig. 1).

GEODYNAMIC IMPLICATIONS

It is important that the experiment used here as a guide be simple. Physical and geometric factors that make it successful are plane-strain indentation "near" a free lateral boundary, the development of faults in deforming plasticine, and the anisotropic layering that has counterparts in Asia in the form of initially approximately southeast-trending Paleozoic and Mesozoic sutures. If grossly correct, the interpretation we present inflates the effects of India's collision with Asia by a factor of perhaps two, and its geodynamic implications should not be underestimated.

Not only can the *boundary forces* involved in *continental collision* activate great overthrusts and large strike-slip faults that develop rifts near their distal extremities, but they can give birth, through the ultimate evolution of these rifts, to fully grown *marginal ocean basins,* sometimes active for a short time. One wonders how slab pull and ridge push can be the main sources of such long-lasting forces.

Uniformitarian theory states that "the present is the key to the past." Yet, extrapolation of present-day motion to the past must be done with caution since *large strike-slip faults,* such as the Red River fault, can *change sense* during continental collision. On the other hand, because we may be looking, in Asia, at successive stages of an extrusion process that repeats itself in time, *the past* may be used as a *key to the present* and future: the opening of the Andaman and South China Seas strongly supports the idea that the Shansi, Baikal, and Yunnan rifts are pure collisional effects, and may themselves evolve into ocean basins if India does not come to a halt. Our experiments suggest that this can occur even *without any driving action by the asthenosphere immediately underneath.*

Faulting may be the *dominant mode of deformation of the continental lithosphere.* In many respects, *fault propagation reconciles intracontinental deformation and plate tectonics.* After a diffuse stage of semicontinuous deformation, where the lithosphere of the collided continent looks for an easy escape, one major strike-slip and rift system, using all convenient lithospheric weaknesses it encounters, propagates to a steady-state "free" plate boundary (for example, a subduction zone). When it reaches this boundary, plate tectonics wins again: a large lithospheric block is extruded and allowed to maintain rigidity, except in and near the region where collision forces drive its motion. Thus, not only paleomagnetism, microtectonics, and stratigraphy but also plate kinematics should help us test quantitatively the story presented here.

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