Relation of the tectonics of eastern China to the India-Eurasia collision: Application of slip-line field theory to large-scale continental tectonics

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ABSTRACT

The active tectonics of northeast China is dominated by strike-slip and normal faulting, with right-lateral motion on north-northeast–trending planes, left-lateral motion on west-northwest–trending planes, and extension in approximately a north-northwest direction. Southeast China, however, is relatively stable. We interpret both the style of deformation in northeast China and the stability of southeast China as consequences of the India-Eurasia collision and the presumably relatively small compressive stress transmitted across the island arcs of the western Pacific. The relationship of the stress field and deformation in eastern China to the India-Eurasia collision are analogous to those in a laterally bounded rigid-plastic medium indented by a rigid die (India).

INTRODUCTION

During the past ten years several destructive earthquakes have focused attention on northeast China. The tectonics of this region contrasts markedly with central and western China, where thrust faulting and high mountains are common (Fig. 1). Northeast China is dominated by strike-slip and normal faulting, and the topography is characterized by large grabens and depressions, bounded by uplifted blocks (Figs. 1, 2). Fault-plane solutions of seven earthquakes, including the July 27, 1976, Tangshan earthquake (Fig. 3), indicate primarily strike-slip faulting: either right-lateral faulting on north-northeast–trending planes or left-lateral faulting on west-northwest–trending planes (Fig. 3; Table 1; Molnar and others, 1973; Molnar and Tapponnier, 1975; Tapponnier and Molnar, 1977). The fault-plane solution for the largest aftershock of the Tangshan earthquake, the only known exception to this pattern, is characterized by normal faulting, but with its T axis poorly constrained (Fig. 3). The Shansi graben (Fig. 2) apparently formed in response to northe...
northwest extension, and its formation appears to include a component of right-lateral motion on the northward-trending planes (Deng and others, 1973; Tapponnier and Molnar, 1977). North and south of the Shansi graben, major west-northwest-trending strike-slip faults can be recognized clearly on LANDSAT photos, and we infer that they are left lateral (Molnar and Tapponnier, 1975; Tapponnier and Molnar, 1977).

Although the Ordos Plateau is aseismic and surrounded by active faults, no simple plate boundary can be recognized in most of northeast China (Fig. 2). The strike-slip faulting occurs on conjugate planes; the aftershock distribution and geodetic surveys show right-lateral faulting on a north-northeast plane during the 1966 Hsingtai sequence (Cardwell and Isacks, 1976; Chen and others, 1975; Geodetic Survey Brigade, 1975), whereas the aftershock distribution and surface faulting indicate left-lateral faulting on a west-northwest plane during the February 4, 1975, Haicheng earthquake (Deng and others, 1976; Wu and others, 1976). Preliminary epicenters of aftershocks of the 1976 Tangshan earthquake suggest right-lateral motion on the north-northeast plane.

All of these observations point to a regional stress system dominated by north-northeast extension. Farther north and west, the orientation of the extension may be more northwesterly, as the orientation of major faults and cinder cones and the distribution of basalt flows in this region imply (Fig. 2; Tapponnier and Molnar, 1977; Terman, 1974).

Although earthquakes have occurred throughout southeastern China in historic times, this region appears to be much less active than most of the rest of China (Fig. 1). Clearly defined recent tectonic features are not conspicuous on the LANDSAT photos (Tapponnier and Molnar, 1977), and the seismicity that has occurred is of small magnitude (Lang and Sun, 1966; Lee and others, 1976; Seismological Committee, 1956; York and others, 1976).

Elsewhere, we interpreted the tectonic activity in Asia as a consequence of the India-Eurasia collision and suggested that the pattern of deformation in Asia is analogous to the deformation of a plane rigid-plastic medium (Eurasia) indented by a rigid die (India) (Molnar and Tapponnier, 1975; Tapponnier and Molnar, 1976, 1977). Our purpose here is to compare in more detail the analogous deformation and stress regime in eastern China to that for another simple plane-strain plastic indentation problem.

**SLIP-LINE FIELDS IN PLANE-STRAIN RIGID-PLASTIC MEDIA**

With the simplifying assumption of plane strain and no strain hardening,

![Figure 2. Simplified tectonic map of northeast China. Heavy lines = major faults recognized on LANDSAT imagery (Tapponnier and Molnar, 1977), hatchures show downdropped side for normal faults; arrows give sense for strike-slip faults; dotted areas = sediment-filled basins, presumably due to normal faulting; diagonal ruled areas = recent basalt flows; asterisks = basalt cinder cones; solid circles = M~8 and open circles = M~7 earthquakes from Chinese historic catalogue. For fault-plane solutions, dark areas = quadrants with compressional first motions, and light areas = dilatational first motions; earthquake dates given (see Table 1). Only three of four solutions from 1966 Hsingtai sequence are shown.](image-url)
plastic flow occurs when the maximum shear stress reaches a limiting value, the yield stress (τy). In a perfectly plastic medium, the shear stress is therefore equal to or less than τy, and deformation is pure shear. Maximum shear stress trajectories, along with τ = τy, intersect each other at 90° and all boundaries free of shear stress at 45°. Slip or shear strain occurs parallel to these trajectories, which are called slip lines. Although the magnitude of the shear stress does not change along slip lines, the mean (hydrostatic) stress does in a simple manner, when the slip lines are curved.

The complete solution to plastic-flow problems requires the specification of the stress and the velocity at every point. For many problems this is very difficult, because with each increment of deformation, the boundaries change shape and the boundary conditions are altered. Often solutions can be given easily only at the onset of yielding. At the same time, at any instant, the stress and velocity fields can be calculated from the boundary conditions at that instant without knowledge of the previous history of deformation. By analogy, in Asia we need not know the previous tectonic history in order to explain the present stress field. The plastic-flow analogy should match this stress field.

Backenofen (1972), Hill (1950), Johnson and others (1970), and Kachanov (1974) have given details on slip-line field theory and how plane-strain rigid-plastic problems can be solved. Essential properties are (1) the slip lines intersect shear-stress-free boundaries at 45°, (2) the shear stress parallel to the slip lines is constant, maximum, and equal to τy = (σ1 - σ3)/2, everywhere in the plastic region, and (3) that the mean stress (σm = (σ1 + σ2 + σ3)/3) changes along the slip lines in a simple manner given by dσm = 2τy dΦ, where dΦ is the change in angle along the slip line, positive when rotated clockwise for α lines (right-lateral sense) and counterclockwise for β lines (left-lateral sense). Thus, if a slip-line field can be found, specification of the yield stress and one of the principal stresses at the boundary of the plastic region allows a complete description of the stress field in the plastic region. Because the slip lines can be lines of discontinuous flow, specification of the slip-line field constrains the possible velocity field. Determination of which slip lines are activated and the complete velocity field required knowledge of the velocity boundary conditions. Not all problems can be posed in this manner, and often one cannot treat the velocity and stress fields independently; however, for the simpler problems of interest here, such a separation is possible.

SLIP-LINE FIELD THEORY AND ASIAN TECTONICS

We (Tapponnier and Molnar, 1976) have attempted to justify the analogy between the tectonics of Asia and plane-strain plastic flow. We compared the deformation in much of Asia, including the Burman arc and the Baikal rift zone, with several plastic plane indentation problems with different boundary conditions. In all of these examples, the rigid-plastic medium extended laterally to infinite distances. Here we consider a problem in which the rigid-plastic medium is finite in the lateral direction (Fig. 4).

In oceanic regions, (rigid) plate tectonics is a very good approximation; only in continental regions does the slip-line field analogy seem to apply on a large scale. The boundaries of the plates presumably represent boundaries of the rigid-plastic medium and it is on them that we apply the boundary conditions. At island arcs, where one plate is subducted beneath another, large compressive stresses do not appear to be transmitted across most arcs. The widespread occurrence of interarc spreading supports this contention. Thus, we assume that the horizontal compressive stress at the island arcs of the western Pacific is negligible small compared with the corresponding stress needed to maintain the elevation of Tibet (Fig. 1). Another type of boundary in eastern Asia, perhaps that which separates the Eurasian and North American plates, may also affect the tectonics of eastern China and serve as a northeast limit to the plastic medium.

We analyze stress and velocity fields for a simple problem, symmetrical and with specially chosen geometry (Fig. 4, a), and then consider more general geometries.
Figure 4. Slip-line fields for simple indentation problems analogous to tectonics of Asia. Diagonal-ruled region is indenter. Arrows show sense of shear on slip lines. Large arrows show direction of rigid motion. a, Simple indentation width of indenter equals half-width of rigid-plastic medium. b, Indentation by narrower block. c, Indentation of quarter space near corner. d, Indentation of medium with oblique boundaries. In c and d, diagram of fault-plane solution and orientation of normal faults shown for analogous deformation with Earth. In c, Mohr circles show states of stress in three regions where \( \sigma_1 \) and \( \sigma_2 \) are both compressive, where \( \sigma_1 \) and \( \sigma_2 \) are compressive, and where \( \sigma_1 \) is negative (tensile). Density of dots decreases from areas of high compressive stress and associated thrust faulting and crustal thickening to areas of tensile stress and associated normal faulting and crustal extension.

(Fig. 4, b, c, and d) and asymmetry (Fig. 4, c and d). The eastern margin of Asia, beneath which the Pacific and Philippine Sea plates descend, is analogous to the boundary of the rigid-plastic medium (free of shear stress) on the right-hand side of Figure 4. a. India corresponds to the indenter. The southern border of Eurasia, east of India, is also a subduction zone and therefore corresponds to a shear-stress-free boundary. Only at the indenter is the normal stress on the boundary large.

The slip-line field in Figure 4, a is identical to that for piercing problems in which a die is pushed into a rigid container in which there is a rigid-plastic material. The indenter moves up with velocity \( V \). In the region OAO', the maximum compressive stress (\( \sigma_2 \)) is oriented parallel to \( V \), and \( \sigma_1 \) is perpendicular to it. The stress axes rotate so that at C and C', \( \sigma_2 \) is perpendicular to the boundaries and \( \sigma_3 \) is parallel to them. Arrows show the sense of shear stress. Near C, left-lateral shear trends northwest and right-lateral shear trends northeast. At B, these are east and north, respectively. At C and C', we assume negligible normal stress, \( \sigma_3 \approx 0 \). Therefore, \( \sigma_1 = -2\tau_y \) and \( \sigma_2 = -\tau_y \). Moving counterclockwise through an angle of \( \pi/2 \) from C to A along a \( \beta \) line (or clockwise from C' to A along an \( \alpha \) line), \( \sigma_2 \) increases by \( 2\tau_y(\pi/2) \). In OAO', where the slip lines are straight, the stress field is uniform: \( \sigma_1 = (\pi - 1)\tau_y \), \( \sigma_1 = \pi\tau_y \), and \( \sigma_3 = (\pi - 2)\tau_y \).

The blocks OCD and O'C'D' do not deform but move rigidly. An increment of displacement of the indenter is accommodated by an upward motion of the triangular block OAO' ("dead" zone). The slip lines parallel to ABC and A'B'C' are activated, as are OA, O'A and their families, so that material in the regions OABC and O'AB'C' deform. The velocities on OA and O'A and on ABC and A'B'C' are discontinuous, but there is no discontinuity in velocity on OC or O'C'. The velocity at OC and O'C' is \( V/\sqrt{2} \) in the directions shown in Figure 4, a.

This problem is particularly simple because of the geometry—the width of the indenter is half the width of the block. For a narrower indenter, the same basic pattern exists, but the slip lines are not all straight lines or circles (Fig. 4, b). The descriptions of the stress and velocity fields given above are similar to those for Figure 4, a, but the ratio of \( \sigma_2 \) at the indenter to \( \tau_y \) is less because of the greater angle swept by the slip lines from the stress-free margin to the dead zone. Also, the velocity of the blocks OCD and O'C'D' is reduced from that in Figure 4, a. (Eventually, when
the width of the rigid-plastic block is large enough, the indentation pressure needed to cause plastic yielding in the area shown becomes larger than that needed for simple plane indentation of a semi-infinite block, and the slip-line field changes drastically to that of simple plane indentation of a semi-infinite medium.)

Deformation in Asia is not symmetrical (Fig. 1). Displacements in central Asia seem to be smaller than in China. Therefore, a more appropriate boundary condition on the left-hand side is that no (or little) displacement occurs at it. In this asymmetrical case (Fig. 4, c) the slip-line field on the right side will be essentially the same as in Figure 4, a, and so will the stress distribution. The velocity field is altered slightly. The material in the region OAO moves to the right rigidly and is deformed in the region OAB as before, but twice as fast. The block OCD still moves to the southeast, also twice as fast (at \(\sqrt{2}V\)).

Each of the slip-line fields in Figure 4, a, b, and c includes one other unnecessary oversimplification, right-angle corners and parallel sides. More realistic boundaries also present no problem. Figure 4, d shows the slip-line field for an oblique boundary. The stress and velocity fields are similar to those in Figure 4, a, b, and c. This more general case may be applicable to northeast China if the boundary between Eurasia and North America is important. The situation in northeast China would then be analogous to that for the Baikal rift zone (Tappornon and Molnar, 1976).

The pattern of deformation near point C in Figure 4, c and d is similar to that in northeast China. Extension is approximately north-northwest, becoming more nearly northwest toward the middle of the plastic zone. Right- and left-lateral strike-slip faulting occur parallel to the trends of the a and b lines, respectively. Moreover, the rigid lower-right corner corresponds to the relatively stable southeast China. In all cases, the principal stresses rotate and decrease in magnitude from A to C (Figs. 4, c), Near A, both \(\sigma_1\) and \(\sigma_3\) are positive (compressive), and mountain building should occur, as it does in the western Gansu. Farther east, \(\sigma_1\) approaches zero, while \(\sigma_2\) and then \(\sigma_3\) become negative. Normal and strike-slip faulting prevail there, with the orientations shown in Figure 4, c. Thus, we suggest that most of the tectonics of northeast China can be explained by secondary tension caused by the indentation of Eurasia by India.

**YIELD STRESS OF NORTHEAST CHINA**

We noted above that in the front of the indenter, in the cases in Figure 4, a and c, \(\sigma_1 = \tau_{xy}\). In a layer 100 km thick, India pushes against the rest of Eurasia with an average compressive stress \(\sigma_3\) of about 500 bar (Tappornon and Molnar, 1976).

(This number would be doubled if the layer were half as thick.) If \(\sigma_2\) is equated to this stress, the \(\gamma_2 = 160\) bar. Even if the layer is only 20 km thick, where deformation is associated primarily with earthquakes, the yield stress is less than 1 kbar.

**SUMMARY**

The tectonics of northeast China are dominated by strike-slip and normal faulting, apparently in response to north-northwest extension. Right-lateral strike-slip faulting occurs on north-northeast planes and left-lateral faulting on west-northwest planes. Southeast China, in contrast, is quite stable. An analogy is drawn between the tectonics and stability of these regions and the deformation and displacement in a two-dimensional rigid-plastic medium bounded laterally and indented at one end near a corner by a rigid indenter (Fig. 4). The slip-line field agrees in sense and orientation with the strike-slip faulting in northeast China and therefore with the inferred orientation of principal stresses. The orientation of the least compressive stress agrees with the direction of extension in regions of normal faulting. The stability of the region analogous to southeast China is predicted also. Thus, we associate the tectonics (or lack of it) in eastern China to the India-Eurasia collision at the Himalaya and to the lack of significant horizontal compressive stress transmitted across the island arcs in the western Pacific.

**REFERENCES CITED**


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