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Right-lateral shear and rotation as the explanation for strike-slip faulting in eastern Tibet

Philip England* & Peter Molnar†

* Department of Earth Sciences, Parks Road, Oxford, OX1 3PR, UK
† Department of Earth, Atmospheric and Planetary Sciences,
Massachusetts Institute of Technology, Cambridge,
Massachusetts 02139, USA

THE convergence of two continents can be accommodated by crustal thickening and by lateral transport of crust out of the path of the converging continents[1–3]. The principal features suggesting that lateral transport is important are major strike-slip faults striking roughly orthogonally to the orientation of convergence between the continents. Displacement on such faults is imagined to allow lateral transport of material with respect to the converging continents, possibly accounting for a large fraction of the convergence between the two continents. The most spectacular example of such strike-slip faulting is in the eastern part of the Tibetan Plateau, where three major left-lateral faults, with slip rates of $>$10 mm yr^{-1}, and several smaller roughly parallel faults dominate the regional strain field[2,3]. Cobbold and Davy[4] suggested that these faults may be rotating in a clockwise fashion. Here we put bounds on that rate of rotation, and conclude that the image of lateral transport on such faults[2], known also as 'continental escape', 'extrusion', or 'expulsion', is an illusion, and that instead the left-lateral slip on east-striking planes in eastern Tibet is a manifestation of north-striking right-lateral simple shear. If this conclusion is correct, the east-striking left-lateral faults and the crustal blocks between them are rotating clockwise at 1–2° Myr^{-1}, the east–west dimension of eastern Tibet is shortening at 10–20 mm yr^{-1}, and little material is moving eastward out of India's path into Eurasia by left-lateral simple shear.

Three major faults dominate the tectonics of eastern Tibet (Fig. 1). Offsets of late Quaternary moraines and erosional features imply Holocene left-lateral slip of at least 20 mm yr^{-1} along the Altyn Tagh fault in western Tibet; the slip rate is probably close to 10 mm yr^{-1} near its eastern extremity[5]. The 30-km offset of ground moraine from its source along the Kunlun, or Xidatan-Tuosuohu-Maqu, fault implies that the Quaternary rate of left-lateral slip along this fault exceeds 10 mm yr^{-1} (ref. 6). Similar offset features[7] and displacements associated with earthquakes in this century[8] suggest a Holocene rate of at least 10 mm yr^{-1} for the Xianshuihe fault (Fig. 1). Holocene and Quaternary slip rates on at least two other, more minor, roughly east-striking left-lateral faults in eastern Tibet are 5–6 mm yr^{-1} (ref. 9) and 6–10 mm yr^{-1} (refs 10, 11). Finally, left-lateral displacements of one to a few metres can be associated with two major earthquakes ($M > 7$) on another two, roughly east-west trending faults in eastern Tibet in this century[8]. Thus, the general impression (see Fig. 2*a*), that the area between 95° E to 105° E and 30° N to 40° N is undergoing major left-lateral shear on roughly east–west-trending planes, is virtually inescapable.

The logical step from recognizing such left-lateral shear to inferring that material is systematically displaced eastward by slip on these faults[2,3,8,12–14] relies on an implicit, and generally unrecognized, assumption that the faults separating blocks of crust do not rotate. Rotations of crustal blocks do occur by slip on curved strike-slip faults in eastern Tibet[14,15], but observations of faulting alone cannot quantify, or even detect, rotations of the faults themselves. If the strike-slip faults rotate about vertical axes, with respect to an external reference frame such as Eurasia, India or southeast China, then the crustal blocks that they separate must also rotate by this additional amount, which can be large[4]. Such rotations, undetected by structural geology, have been demonstrated clearly by palaeomagnetic results from several other regions of continental deformation[16–18].

Suppose that eastern Tibet underwent shear in a right-lateral sense along a north–south-trending zone. In such a zone, the roughly east-trending blocks and the faults separating them (Fig. 1) would rotate clockwise, slip on the faults would be left-lateral, and the eastern and western margins of the zone would approach each other[19] (Fig. 2*b*).

Common sense, unburdened by a knowledge of the faulting in eastern Tibet, would lead to the inference of such north-trending, right-lateral simple shear. The eastern part of India moves nearly due north at 50–60 mm yr^{-1} with respect to Eurasia[20]. India underthrusts southern Tibet, also nearly due north[15,21], at between 10 and 25 mm yr^{-1} (refs 22, 23). Hence, southern Tibet, just north of eastern India, moves northward at 25–50 mm yr^{-1} with respect to Eurasia. Southeast China, the area east of eastern Tibet, is surely not rigidly attached to Eurasia, but the following argument shows that its northward component of velocity with respect to Eurasia is a small fraction of that of southern Tibet ($\leq$10 mm yr^{-1}). All known major active structures between southeast China and eastern Siberia reflect strike-slip or normal faulting[2,3,24,25]. Slip on these structures may allow southeast China to move east or southeast with respect to Eurasia[8,12,14,26] but would not permit a northward translation of southeast China with respect to Eurasia. The western part of southeast China could be moving northwards with respect to Eurasia, whereas the northern part would not if there were rapid ($>$1° Myr^{-1}) clockwise rotation of southern China about an axis within southeast China. The hypothesis of a rapid clockwise rotation of southern China is difficult to test, not least because the extent of the block containing southern China is hard to ascertain. If that block extended as far south as the Banda arc then the hypothesis would seem to be incorrect, because the slip vectors of earthquakes in the western Banda arc[27] would imply anticlockwise rotation of the block. In the absence of a more definitive test, we presume that rapid clockwise rotation of southeast China does not occur.

With that assumption, the northward component of southern Tibet's velocity with respect to western southeast China should be at least 15 mm yr^{-1} (and could be substantially $>$ 30 mm yr^{-1} and eastern Tibet is undergoing a significant component of regional north-trending, right-lateral simple shear. Note that such right-lateral shear is found in both numerical and laboratory experiments of deformation of a variety of media subjected to an indenting boundary condition, such as India applies to Asia[4,12,14,26,28–34].

We may test the hypothesis that north–south dextral shear is distributed across the region by using the difference across the zone in the north–south component of velocity to calculate the rate of rotation of the blocks and the rate and sense of shear on their bounding faults. Consider a rectangular region encompassing eastern Tibet, roughly 1,200 km in its north–south dimension and 1,000 km east–west (Fig. 1). Let us ignore the likely variations in the style of deformation and in the orientations of the faults, treating the deformation as homogeneous throughout the region. (We will discuss the complexities of the deformation elsewhere.) The rate of rotation of the blocks and the faults bounding them is given by the north–south component of the velocity difference across the zone, divided by the east–west width of the zone (~1,000 km). Above, we estimate that the north–south component of the velocity difference is 15–30 mm yr^{-1}. The rate of rotation due to this velocity difference is between 1 and 2° Myr^{-1}. The corresponding cumulative rate of left-lateral slip on east-southeast to southeast-trending faults is 20–50 mm yr^{-1} over the whole zone, or roughly 10 mm yr^{-1} on each of the major faults. Hence, the calculated cumulative left-lateral shear agrees with the sum of measured slip rates on faults in eastern Tibet.

Because the major faults in this region are all vertical strike-slip faults, shortening of one dimension must be associated with

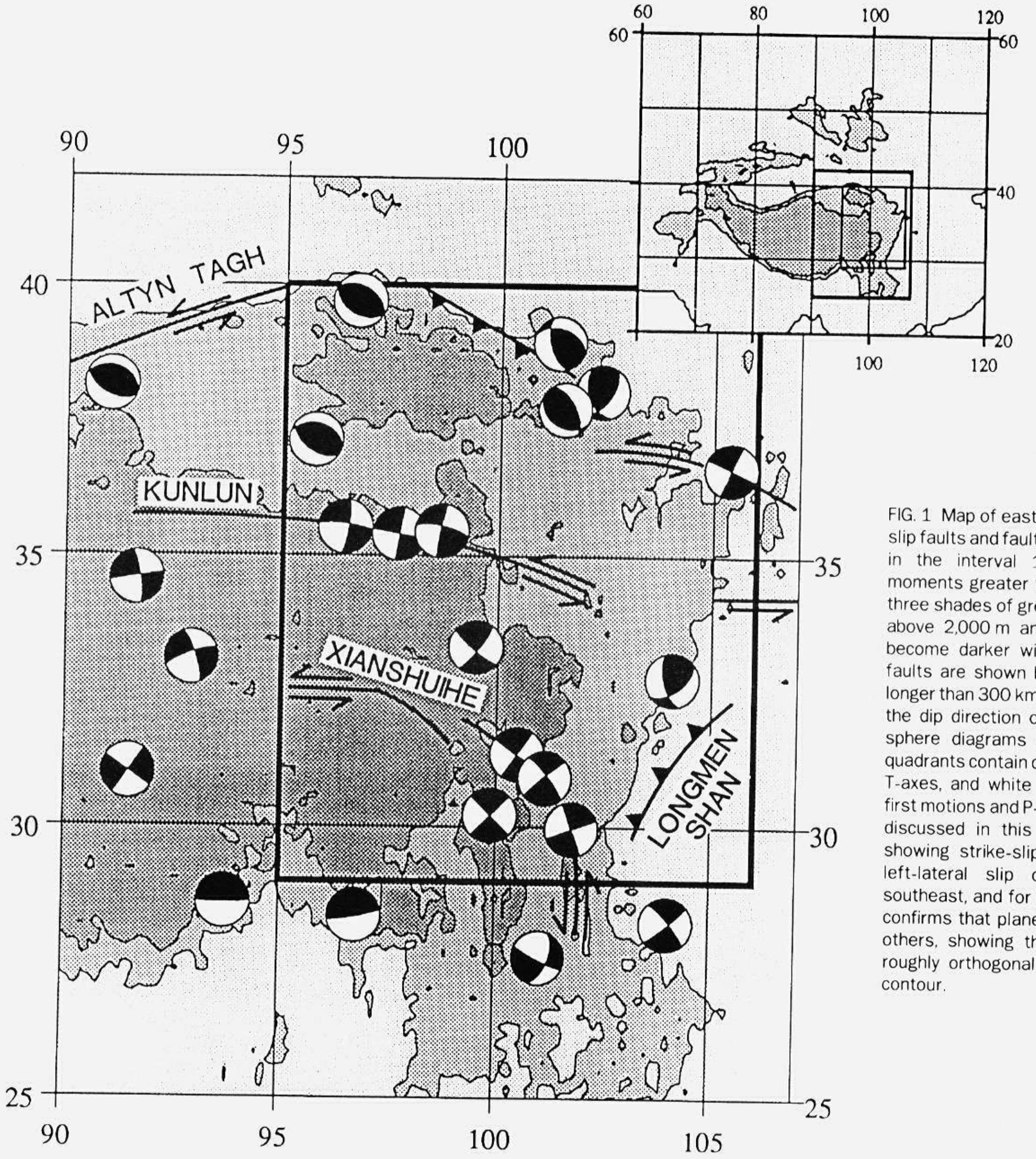

FIG. 1 Map of eastern Tibet, showing major strike-slip faults and fault-plane solutions of earthquakes in the interval 1900 to 1987 with seismic moments greater than 10^{18} N m (refs 8, 15). The three shades of grey indicate land above sea level, above 2,000 m and above 4,000 m; the shades become darker with increasing elevation. Major faults are shown by dark black lines; only faults longer than 300 km are included, and teeth indicate the dip direction of thrust faults. In lower-hemisphere diagrams of fault-plane solutions, dark quadrants contain compressional first motions and T-axes, and white quadrants contain dilatational first motions and P-axes. All solutions in the region discussed in this paper (95–105° E, 29–40° N) showing strike-slip faulting are consistent with left-lateral slip on a plane trending east-southeast, and for most of them, surface faulting confirms that plane to be the fault plane. For the others, showing thrust faulting, the P-axes are roughly orthogonal to the trend of the 2,000-m contour.

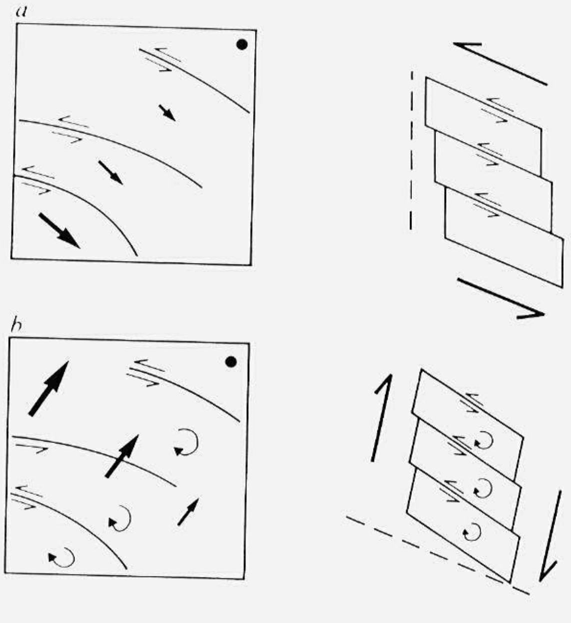

FIG. 2 Sketches of contrasting interpretations of the faulting in eastern Tibet. For *a* and *b*, the left figure shows locations and senses of slip on idealized faults with the inferred velocity field corresponding to the simple interpretation on the right. The velocities are drawn with respect to a fixed point in the upper right-hand corner. In *a*, as slip occurs, the faults do not rotate with respect to the surrounding material. Left-lateral slip leads to an east-southeastward translation of material on the south side of each fault relative to material on the north side. The sum of slip rates on the faults would give the rate at which material in the south is translated east-southeastward with respect to the material in the north. In *b*, the eastern boundary of the region defines the fixed reference frame, and the left-lateral slip is a manifestation of north-trending right-lateral shear of the region and clockwise rotation of the blocks between the left-lateral faults. Note that for the east-southeasterly strikes of the faults, the continued rotation and slip on these faults leads to a shortening of the east–west dimension and a lengthening of the north–south dimension[4,19,35,36].

perpendicular extension[19,35,36]. Clearly, this shortening is orientated neither perpendicular to nor parallel to the strike-slip faults. Most of the left-lateral faults, south of the Altyn Tagh fault, strike east-southeast or southeast (110°–135°), and consequently, the clockwise rotation of blocks leads to a shortening of the east–west dimension and a lengthening in the north–south dimension[4]. The rate of east–west shortening is given by the north–south component of the velocity difference divided by the tangent of the strike of the faults. Hence the western margin of eastern Tibet (near 95° E) should move eastwards with respect to the eastern margin (near 105° E) at about 10–20 mm yr^{-1}.

We may now investigate quantitatively the question of whether southern China is[2], or is not[4], being displaced eastward with respect to Eurasia by sinistral slip on the major faults in Eastern Tibet. The western margin of eastern Tibet is moving eastwards with respect to Eurasia at an estimated rate of between 10 and 30 mm yr^{-1} (see for instance, refs 13, 15 and 26). If the velocity field of Fig. 2*a* is accepted we must add 20–40 mm yr^{-1} to this rate to calculate the rate of eastward displacement of southeasternmost Tibet (the Longmen Shan in Fig. 2) with respect to Eurasia. By contrast, if the velocity field of Fig. 2*b* is accepted, we must subtract 10–20 mm yr^{-1} to calculate that rate. If the first calculation (Fig. 2*a*) is performed, it seems that easternmost Tibet (and presumably southern China) is moving eastward with respect to Eurasia at several centimetres a year. If the second calculation (Fig. 2*b*) is performed, one concludes that southern China may be moving east with respect to Eurasia by at most a couple of centimetres a year—or may, in fact, not be moving eastward with respect to Eurasia at all. Thus the image[2] of rapid eastward 'expulsion' or 'extrusion' of southern China with respect to Eurasia cannot be sustained if the faults in eastern Tibet are rotating clockwise at more than about 1° Myr^{-1}—as our calculation of the rate of north–south dextral shear of the region suggests they are.

One might ask why the surface crust in a zone of north-trending, right-lateral shear deforms by displacements and rotations of blocks of crust bounded by roughly east-striking faults. Pre-existing weaknesses that formed both before India collided with Eurasia and later, when its penetration caused north–south shortening of southern Eurasia, probably trended roughly easterly. The palaeogeography of southern Eurasia[38] reveals several east-trending Mesozoic sutures across Tibet, and both numerical[28–34,38] and laboratory[4] experiments of continuous media in a gravity field show shortening in a north-to northeast-trending zone. The change from largely crustal shortening in Tibet to east–west extension in late Cenozoic time should have enhanced the eastward component of displacement[30] and might have encouraged left-lateral slip on these pre-existing weak zones. This explanation suggests that left-lateral faulting in eastern Tibet became significant only after east–west extension of Tibet began. If this is so, the rotations suggested here would be on the limit of detection by palaeomagnetic means, but will eventually be detectable by space geodetic techniques. Should the rotations and right-lateral shear in eastern Tibet prove to be difficult to measure, either with palaeomagnetism or with space geodesy, then an alternative is to test the basic assumption that the western margin of southeastern China does not move northward with respect to Eurasia at more than ~10 mm yr^{-1}.

The absence, hitherto, of inferences of clockwise rotation of faults and of north-trending right-lateral shear in eastern Tibet calls attention to a general aspect of continental tectonics. As stated clearly by McKenzie and Jackson[19–23,35–37], structural geology and seismology share a fundamental weakness in the study of tectonics, because they are poorly equipped to detect rotations of faults about vertical axes. It would be folly to suggest that the orientations and rates of slip on major faults are not important in describing the kinematics of regional deformation, but a description of deformation derived solely from faulting, however how high the rates of slip, can give a very misleading impression of the velocity field of deforming continental lithosphere. □

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