Relatively recent construction of the Tien Shan inferred from GPS measurements of present-day crustal deformation rates


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The Tien Shan—a high, seismically active intracontinental mountain belt, 1,000–2,000 km north of the Himalayas—has grown as a result of India’s collision with Asia1. The crustal shortening (~200 ± 50 km; refs 2, 3) and thickening that gave rise to the Tien Shan accommodates only a small fraction of India’s total penetration into Asia (2,000–3,000 km), and the temporal relationship of deformation in this belt to the India–Asia collision remains unclear. Here we report geodetic measurements of the Tien Shan, using the Global Positioning System (GPS), that indicate that the current crustal shortening rate is nearly half of India’s convergence rate with Eurasia in this area4. We infer a total shortening rate for the Tien Shan of ~20 mm yr−1, which is approximately twice that inferred previously from the extrapolation of slip rates in the Holocene and earthquake-induced displacements during this century5, suggesting that the rate of mountain building in this region has accelerated several-fold since the onset of collision ~50–55 Myr ago6. If, as we argue, the current shortening rate can be extrapolated to geological timescales, then our results suggest that most of the Tien Shan has been constructed during the past 10 Myr, perhaps in response to an increased horizontal force following an abrupt rise of the Tibetan plateau7.

The Tien Shan, some 2,500 km long and 300–500 km wide, forms a typical intracontinental mountain belt, far from either the locus of collision between continents or a subduction zone (Fig. 1), although it is a consequence of the collision between India and the rest of Eurasia. Within the belt, thrust or reverse faults, without a consistent vergence, separate east–westerly trending ranges and basins, some of which contain 2 km or more of late Cenozoic sediments8–14. Fault plane solutions of earthquakes15–19, surface ruptures of two major earthquakes20,21, and widespread Holocene faulting and folding22–26 attests to continued thrust faulting and crustal shortening throughout the Tien Shan.

Although strain within the Tien Shan accommodates India’s penetration into the rest of Eurasia, the temporal relationship of deformation to the collision is not clear. Intense Paleozoic deformation occurred in the area that includes the present Tien Shan2, and transport directions of water flow inferred from Mesozic fluvial sediment adjacent to the present mountain belt imply early and middle Mesozic relief23. Yet the present high topography appears to be Cenozoic in age; early Cenozoic (and rare late Cretaceous) sedimentary strata conformably overlie flat, but tilted, erosional surfaces on individual ranges and collectively define a ‘pre-orogenic surface’ with little early Cenozoic relief23–25. Variations in thicknesses of late Oligocene and early Miocene sediments suggest the subsequent development of relief, a result consistent with cooling ages of rock exposed in the eastern Tien Shan26–28. A progressive thickening of the late Cenozoic sedimentary section in basins within the Tien Shan, led several workers to deduce that deformation accelerated in late Cenozoic time29–32. Because of uncertainties in dating continental deposits and large changes in the geological timescale since much of this work was done, however, it has been impossible to quantify such an inference of acceleration. For instance, Avouac et al.3 extrapolated their estimated rate of Holocene shortening across part of the Tien Shan to infer an initiation of deformation at ~20 (~30/–10) Myr, but the large uncertainties of both the Holocene rate and the total shortening prohibit placing tight constraints on the time of initiation of mountain building in the belt.

The relief, distribution of active faults, and seismicity indicate that deformation has been distributed across the Tien Shan (Fig. 1). This contrasts with subduction zones, where a localized thrust zone marks the boundary between two plates, and with collision zones, where one continent has plunged beneath another along a major thrust fault, as has occurred in the development of the Alps33 or Himalayas34. In these respects, the Tien Shan typifies intracontinental mountain belts, like the Nan Shan, Altay, or Gobi-Altay in Asia35,36, the Atlas Mountains of North Africa, the Sierra Pampeusae of the Argentine Andes37, the Laramie Rocky Mountains of the western United States38, and perhaps the Tibetan plateau in its initial stages of Cenozoic development. In the segment of the Tien Shan shown in Fig. 1, a typical fold-and-thrust belt is underscored by its association with (1) the marked flexure of the Tarim Basin, which requires a significant load39; (2) the highest rates of current seismicity in the Tien Shan; and (3) the highest range in this segment of the Tien Shan.

To measure the present-day kinematics of deformation, we established an 86-station GPS network in the Republics of Kyrgyzstan and Kazakhstan (Fig. 1). The network shares sites with a regional-scale network established by a collaboration of German scientists from the GeoForschungsZentrum and local scientists, including some of us40. Here we rely on measurements from a small part of the 86-site network made in 1992, but also, and more importantly, on measurements made in the central and eastern parts of the network in 1993, and twice in 1995 (Fig. 1).

We processed the data in three stages41. In the first, we used carrier phases to estimate three-dimensional (3D) coordinates of all sites, parameters representing the satellites’ orbits, and other miscellaneous parameters needed to model GPS phase data. For each day of data collection, we processed recordings from a global network of 27–40 tracking sites and, separately, a regional network with two to three global sites included. Until the second campaign in 1995, all global sites lay well outside the Tien Shan. For that campaign, we included one of the newly installed continuously operating stations in the Tien Shan (POL2) in the analysis of global stations. The GPS biases were resolved to integer values for the regional stations but not in the global analyses41.

In the second stage, we combined 3D station coordinate estimates and satellite orbit parameters, with their full covariance matrices, and used a Kalman filter estimator42 to obtain optimum
estimates of the 3D site coordinates for each campaign. To avoid singularities in this analysis, we constrained all site coordinates weakly, to be within 100 m of estimated coordinates, after which satellite orbit parameters are no longer needed.

In the third stage, we did two types of analysis. In one, we combined estimates of the 3D site positions from each campaign to estimate simultaneously the 3D site coordinates and velocities, with weak constraints on both: <100 m and <1 m yr\(^{-1}\), respectively. To this solution, we applied generalized constraints to the rigid-body rotation and translation of its coordinate system to minimize the differences in the horizontal velocities between the observed and previously determined velocities at 13 global sites. This analysis formed our velocity solution, presented with respect to AZOK on the Kazakh Platform (Fig. 1). In a second type of analysis, we considered campaign solutions separately with the coordinates of the 13 global sites constrained to lie within a few millimetres of their estimated positions for each campaign epoch. For this analysis, we generated time-series plots for the coordinates of the regional sites (Fig. 2).

The observed velocity field (Fig. 1) documents strain across the belt from the Kazakh Platform, north of the belt, to the segment near the border with China. Rates range from near zero, in the north, to a maximum at the southern edge of the network of 13 ± 2 mmyr\(^{-1}\) (Figs 2 and 3), and directions are essentially parallel to the convergence between the Indian and Eurasian plates\(^{1}\). Because our estimated rate at which AZOK moves with respect to Eurasia—1.7 ± 3 mmyr\(^{-1}\) towards N10° W—is not resolvable, we conclude that only minor plate convergence is absorbed north of AZOK. Our data do not indicate areas of localized high or low strain rates, except on the eastern profile (Fig. 3), although the large uncertainties in rates cast some doubt on the magnitudes of strain rates there. Within the interior of the belt, especially along the profile in the 76°–77° band, the uniform variation in north–south speed across the Tien Shan implies a roughly homogeneous strain field. The small variation in northward speeds across the network (Fig. 3) suggests that rates across individual faults within the Tien Shan do not exceed a few mmyr\(^{-1}\). Thus, the distribution of strain accumulation concurs with the geological and seismological observations of active deformation throughout the Tien Shan\(^{3–13,15–22}\).

Because our network spans only ~70% of the width of the Tien Shan, as measured from the Kazakh Platform across the belt to the Tarim Basin, 13 ± 2 mmyr\(^{-1}\) underestimates the total convergence rate across the belt. A simple extrapolation implies a total convergence rate of ~20 mmyr\(^{-1}\) between the Tarim Basin and the Kazakh Platform. Such an extrapolation seems reasonable, given both the nearly constant strain rate that we measure (Fig. 3) and the particularly high terrain, high seismicity and marked flexure of the Tarim lithosphere south of our network. In fact, geological mapping of a fold-and-thrust belt at the southern edge of the Tien Shan ~500 km east of our network suggests an average Quaternary shortening rate across it of between 4 and 14 mmyr\(^{-1}\) (B. C. Burchfiel et al., manuscript in preparation), consistent with such an extrapolation. This rapid convergence across the Tien Shan supports the contention that crustal shortening and thickening built the present Tien Shan, with thermal processes associated
with asthenospheric upwelling³⁵ playing at most a minor role.

The shortening rate of ~20 mm yr⁻¹ across the Tien Shan exceeds previous estimates³⁵ by 50–100%. Seismic moments of earthquakes suggest shortening at an average rate of 10 (±3) mm yr⁻¹ in this century (ref. 5, and our unpublished work). The high rate of convergence therefore implies either a significant proportion of aseismic strain in the Tien Shan or a deficit in the seismic slip this century, which might indicate a heightened risk of a major earthquake occurring somewhere in the Tien Shan. The apparently uniform strain accumulation across the Tien Shan implies that the risk of such an event is not restricted to the northern or southern margins of the belt, but could occur on virtually any of the major thrust faults within the belt.

The shortening rate of 13 ± 2 mm yr⁻¹ strictly applies for only ~2 yr. Observations from elsewhere, however, show agreement between rates estimated geodetically for distances sufficiently long that elastic strain is minor and average rates for geodetic timescales. For instance, geodetically determined slip rates for the San Andreas fault³⁶ and Sieh and Jahn's⁵⁵ average Holocene rate differ by less than the uncertainties of a few mm yr⁻¹ in each. Similarly, determinations of plate motions from magnetic anomalies since 2 Myr differ by a few mm yr⁻¹, at most from those estimated using space geodetic techniques for 5–10 yr (ref. 37). Moreover, on a regional scale, the convergence rate between India and Eurasia has varied insignificantly, by no more than a few mm yr⁻¹, since their collision.²⁵ Nevertheless, because we cannot eliminate the possibility that large, essentially rigid blocks, such as that beneath the Tarim Basin, move erratically and not steadily with respect to their neighbours, the equating of a 2-year average rate with a several million year average carries a risk that cannot be evaluated at present. We ignore such a possibility here.

The observed shortening across the western Tien Shan at ~20 mm yr⁻¹ may be used to estimate the timescale for Cenozoic crustal shortening in the Tien Shan. Assuming that thick crust compensates for the high elevations of the Tien Shan, and that Airy isostasy holds at least approximately, Ulomov³⁶ and Avouac et al.⁶ estimated 200 (±50) km of Cenozoic shortening. At a roughly constant shortening rate of 20 mm yr⁻¹, the entire belt could have been built in ~10 Myr. If deformation began as early as 20–30 Myr, it must have accelerated by several times since that time, as Goryachev³⁶ and Makarov³⁶ suggested. If a hot uppermost mantle compensated for part of the topography,³⁶ even less shortening would have occurred, and the acceleration could be even younger. Makarov³⁶, in fact, inferred from a synthesis of faulting that the total Cenozoic shortening across the belt does not exceed 50 km, which would call for a very recent acceleration of deformation. Regardless of the total amount of shortening, the terrain comprising the Tien Shan appears to have developed long after India collided with Eurasia, by rapid shortening distributed both within and along the margins of the belt. Timing of the change from normal to thrust faulting in Tibet, of climate change in Asia possibly due to a rapid uplift of the plateau, and of north-south shortening within the Indian plate south of India, all at ~8 Myr, suggest that the Tibetan plateau rose abruptly by 1–2.5 km in only a few million years.³⁶ A roughly 10-Myr onset of rapid growth of the Tien Shan might result from the increase in the force transmitted by a higher Tibetan plateau to its surroundings.²⁵

Received 21 May; accepted 22 October 1996.


**FIG. 3** Profiles of north-south components of velocity across the region along four profiles, measured with respect to station AZOK, one of the two northernmost points on the 77–78 degree band. Speeds increase southwards, showing north-south shortening across the region and, for most profiles roughly uniform strain. Speeds in northern areas exceed those in the eastern profiles. (different local strain) but may also be an error (note the large uncertainty).

ACKNOWLEDGEMENTS. We regret that we cannot thank individually the nearly 100 people who contributed to the gathering of the data reported here. P. A. Astakhovich, V. Bragin, S. Fisher, V. F. Kopachev, M. Khazaen, V. A. Kuzmin, N. Neklon, V. V. Obridenko, V. Z. Ostrov, B. Petru, G. Shrotechov, N. A. Shcherbakov and J. Stowell provided special help with logistics and guidance; R. Ranka, V. Galan, T. Gussar, V. Kolos, M. Minguashev, V. Pecorelo and P. Yermeyev took leading roles in the installation of the network. We thank UNAVCO for assistance in all aspects of operation, and in particular engineers D. Meman, N. Normando and B. O'Neill for training us and making on-the-spot repairs; C. Rigney for sharing data measured by his group; R. Burgmann, P. Lobold and J. Keppe for critically reviewing the manuscript and S. McDowell for Fig. 1a. This work was supported in part by NASA and by the NSF.