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Crustal shortening during mountain building: A case study in the Pamir–Tien Shan and Altay–Mongolia region

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Abstract. Unravelling the underlying causes of mountain building is one pivotal issue of geotectonics. The most popular model invokes crustal thickening through horizontal, across mountain ranges, contraction of the area occupied by a mountainous country with its ensuing isostatic uplift. Another model calls for crustal underplating due to either underthrusting or to melts derived from mantle plumes, also resulting, through isostatic mechanisms, in mountain building. The objective of this paper is to establish relations between these two likely processes using case studies from the Pamir–Tien Shan region, as well as Altay and Mongolia. In tackling this problem, two methods are employed to define the amount of crustal shortening. Method 1 draws on crustal thickness as a starting value, and shortening is calculated as a function of its increase relative to the initial "cratonic" thickness. In contrast to well-known approaches, geometric characteristics of magnitudes of neotectonic movements used in this algorithm enable one to establish the direction of maximum shortening and the relation between maximum and minimum shortenings. A data base on Moho depths and neotectonic movement magnitudes from Tien Shan was used. The N–S crustal shortening was found to be between 12% and 25% for Tien Shan. Method 2 is a modification of routine calculations based on folding and faulting deformations of peneplanation surfaces. Shortening values thus obtained were 4–12% on average for Tien Shan, 35% to 60% for the Afghan–Tajik basin, and less than 1% for Pamir, whereas Altay, Sayan, and Mongolia yielded both extension and shortening of 0.1% to 1.2%. Comparison of crustal shortening values obtained for Tien Shan by the two different methods shows a match of results obtained from maximum shortening directions and from spatial distribution of shortening maxima. A good correlation of these values was established, which is interpreted to show the model of crustal shortening and thickening (Method 1) to be in keeping with the natural process. Analyzing the regression of paired shortening values shows that lack of shortening from peneplanation surface deformations corresponds to a crustal thickening of 7 km on average across Tien Shan. This is interpreted to suggest that, in Tien Shan, the two mountain building processes, horizontal shortening and crustal underplating, are in operation concomitantly. Therefore, one cause of mountain building in Tien Shan is pressure exerted by Pamir and Tarim and transmitted 300–400 km northward from their boundary. In Mongolia, Sayan, and Altay alike, mountain building might be driven by the same causes related to rifting. Crustal shortening data rule out any impact from the Indian subcontinent pressing northward.

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Introduction

Crustal shortening during mountain building is an extremely puzzling issue because, more often than not, geological history of structures involved in mobile belts can only tentatively be subdivided into stages with contrasting types

Figure 1. Physical map of central and southern Asia showing the study areas, (A) Pamir–Tien Shan and (B) Mongolia–Altay.

and amounts of deformation. In addition, several methods to determine the amount of shortening are available that differ perceptibly in the character of material used. This should be accounted for in the course of the geodynamic analysis of miscellaneous data obtained by researchers, which is not always a trifling problem. Thus, one should distinguish between folding and mountain building, because in many regions these two phenomena are well apart in time, and small-scale folding differs clearly in its mechanism and scale from basement folds that form individual mountain ranges ("plis de fond" of Argand). On the other hand, attempts of in-depth insight into deformation mechanisms result inevitably in geological history being subdivided into individual stages, and the major structure, into its constituent parts that have dissimilar formative mechanisms at various stages of their respective histories.

In the mid-20th century, the geosynclinal paradigm was dominant, in whose framework the origin of folding was explained without invoking regional crustal shortening [*Belousov and Sholpo,* 1976; *van Bemmelen,* 1933; *Goncharov,* 1988; *Gravity...,* 1976; *Ramberg,* 1981; *Sholpo,* 1978]. Gradual accrual of data on the character and mechanism of folding deformation proper and the advent of plate tectonics resulted in that, at present, crustal shortening across mobile belts is, at a qualitative level, a thoroughly proven fact. In this connection, let us consider briefly the main trends of various studies concerning crustal shortening in order to understand, in this context, implications of our own assessments for particular regions.

Reconstructions for regional and relatively local structures, which are very common in literature and which draw on the analysis of depositional history and timing of displacement of thrust sheets and folding, stem from traditional geological methods (e.g., [*Dercourt et al.,* 1986]). Present-day reconstructions for local structures are largely based on section balance methods using data from geological observations, drilling, and detailed geophysical surveys. These methods [*Gibbs,* 1990; *Hossack,* 1979; *Woodward et al.,* 1989] afford a more refined structural picture and yield amounts of horizontal displacement whose accuracy depends on input data. Thus, for the northeastern Carpathians, [*Behrmann et al.,* 2000] obtained one of the greatest values of crustal shortening, 260 km over the period from the Middle Oligocene to Middle Miocene, in a NE–SW direction between the European craton and the inner Carpathians.

A similar approach is used in studies that draw on paleomagnetic data. They may yield two sorts of material that affords assessment of shortening: coeval paleolatitudes for opposite margins of an E–W trending structure that underwent shortening and a set of coeval poleward directions in structures that are bent in plan view [*Bazhenov and Burtman,* 1986; *Burtman,* 2000; *Burtman et al.,* 1998]. Note that the accuracy of paleolatitude measurements is not usually very good (2°–5°), and they are thus significant only with very large displacements, whereas data on rotations greater than 10° are, as a rule, deemed reliable and may provide interesting material for relatively small-scale structures [*Bazhenov,* 1988]. Such data are supplemented by studies of the width and completeness of the set of facies zones in structures with well-developed thrusts and by the analysis of detailed cross sections [*Burtman,* 2000], enabling the amount of displacement to be assessed from the width of facies zones overlapped completely by thrust sheets.

To calculate crustal shortening during mountain building, two principal methods are used, whose results can be compared. These are, primarily, calculations assuming that shortening of the crust involves a corresponding amount of its thickening. In these calculations, one must know the modern crustal thickness and assume its value prior to mountain building [*Avouac et al.,* 1993; *Billings,* 1960].

Method 2 postulates a constant length of peneplanation surfaces, which undergo folding deformations, faulting, and thrusting, and makes use of geological and geomorphologic profiles [*Chediya,* 1986]. Both methods will be addressed in detail below.

Lastly, a certain importance is attached to shortening assessments based on direct measurements of displacements of geodetic stations over several tens of years [*Guseva et al.,* 1993, 1999; *Shevchenko et. al.,* 2000], including those involving GPS [*Abdrakhmanov et al.,* 1996; *Prilepin et al.,* 1997]. Another method affording this sort of measurements is based on one or another procedure of measuring seismotectonic deformations, chiefly from earthquake mechanisms [*Lukk et al.,* 1995].

Assessments of crustal shortening during mountain building from geological data depend strongly on which models for the structure and development of the entities under study are employed. Usually, these assessments indicate 5–15% shortening, and for many Alpine orogens shortening is assessed at the characteristic value of 50–60 km [*Gravity...,* 1976; *Scheidegger,* 1987; *Stoecklin,* 1977]. However, some areas of intense neotectonism exhibit perceptibly increased crustal thicknesses, even though corresponding amounts of crustal shortening can hardly be inferred because peneplanation surfaces are considerably uplifted, but virtually undeformed (e.g., the Tibet Plateau and eastern Pamir). For this reason, the choice of causes (models) for mountain building ranges from mechanical deformations (shortening vs. extension) and processes of buildup and destruction of the lower crustal portion. Accordingly, the issue of choice is linked tightly to how reliably orogenic crust shortening (extension) has been quantified. In this context, geological history of the region plays a significant role. Thus, in Tien Shan the onset of mountain building was preceded by a lengthy quiescent period, and well-developed peneplanation surfaces were formed in a cratonic environment and at a "standard" crustal thickness. For the Caucasus, the main orogenic movements, which resulted in 50–60% horizontal shortening, are inferred to have terminated shortly before the uplifting of the orogen proper. In other words, crustal thickening and uplift here prove to be separated in time. On the other hand, evidence exists that folding has not yet stopped completely throughout the area.

Historically, the first mountain building model to appear invoked horizontal shortening of the crust leading to its proportionate thickening, which, in terms of the isostatic scheme, is associated with uplifting of its surface [*Billings,* 1960]. Another model calls for a mantle diapir (plume) being emplaced into the upper mantle and crustal underplating due to melts of relatively light weight material [*Grachev,* 1999], also resulting in isostatic uplifting of orogens. The first model can be tested by establishing relations between the measured horizontal shortening and crustal thicknesses, while the second draws on seismic tomography and chemical geodynamics data.

For the purpose of this study, to analyze in what measure crustal shortening assessments may support one or another mountain building hypothesis, we chose the Pamir–Tien Shan region in combination with the Altay–Mongolia one (Figure 1). Importantly, case studies from the area have been repeatedly used by researchers, beginning with [*Argand,* 1924], while discussing various geodynamic models and mountain building hypotheses. Lately, in connection with geodynamic models developed on the basis of plate tectonics, this area has frequently been the focus of study. Thus, [*Avouac et al.,* 1993], based on calculations of crustal shortening and assuming crustal thickening, put forward a model in which Tien Shan, in the course of mountain building driven by pressure exerted by Pamir, rotated 7° counterclockwise. To test how strongly mountain building is re-

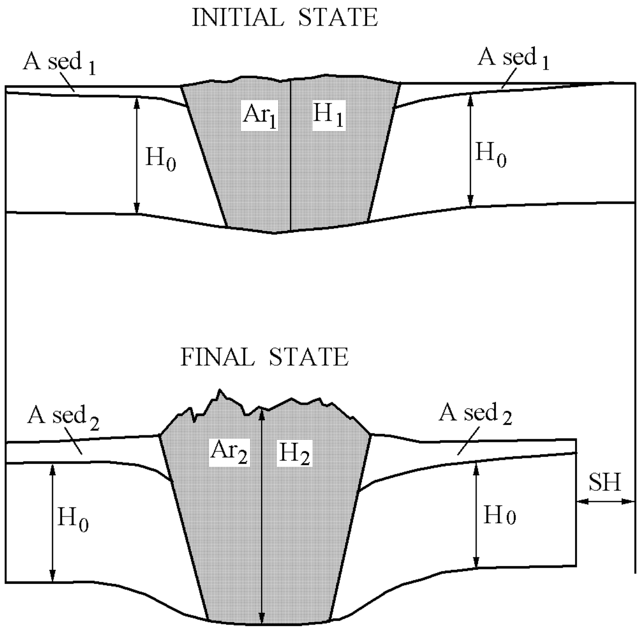

Figure 2. Previous scheme of crustal shortening determination from crustal thickening, after [*Avouac et al.,* 1993].

lated to plate motions, we studied the distribution of impact from the collision of the Indian and Eurasian plates, measuring for this purpose the amounts of crustal shortening in the Pamir–Tien Shan region and Mongolia [*Grachev,* 2000]. Our measurements involved the use of two methods and two dissimilar data sets.

Methods Used

Determining Crustal Shortening that Leads to Crustal Thickening

The method is based on the aforementioned concept of crustal thickening during crustal shortening [*Avouac et al.,* 1993] (Figure 2), and it was used to determine the maximum crustal shortening and its direction in Tien Shan.

The procedure of calculating deformation includes a quantitative analysis of vertical neotectonic movements and depths to Moho. The calculation of deformation involves comparison of geometries of a unit volume in the initial and final states, respectively, assuming this volume to be constant, which, needless to say, is not quite correct.

Assume that the height of the unit volume with account for the initial depth to Moho H_{M0} is $H_0 = H_{\mathrm{M0}}$ in the initial state (in our case, $H_{\mathrm{M0}} = 40$ km), and the total average effect from vertical neotectonic movements N_{v} with the depth to Moho in the final state H_{M} yields the height of the unit volume $H = N_{\mathrm{v}} + H_{\mathrm{M}}$. Deformation in the vertical direction will then be E_z :

$$E_z = (H - H_0)/H_0 \ .$$

Crustal shortening can be quantified in the horizontal plane on the basis of data on vertical neotectonic movements in a compressional environment. Deformation along a certain horizontal direction L can be reconstructed by relating the present length L to the initial length L_0. Reconstruction consists in "unfolding" the relief generated by vertical neotectonic movements over the corresponding section L in point of the profile. In this way, one can calculate components of deformations along assigned horizontal directions, evaluate components of the planar deformation tensor on this basis, and, lastly, determine the values of the main deformations and directions thereof (Figure 3), with the main deformations E_1 and E_2 being negative values that correspond to horizontal crustal shortenings along the respective main directions. Clearly enough, these deformations were calculated, in fact, with an accuracy to within a certain coefficient K, because they are not complete. This coefficient

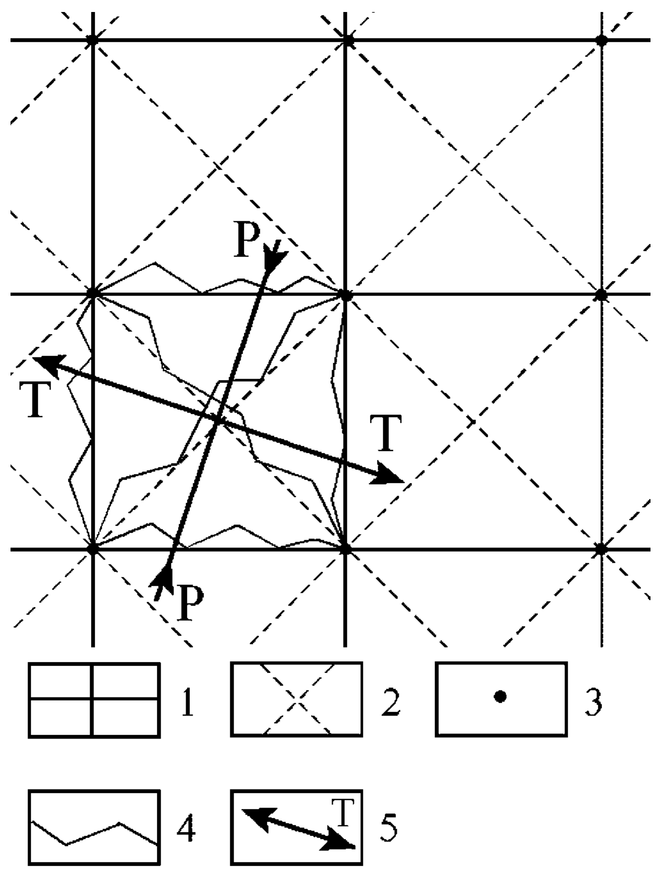

Figure 3. Schematic representation of calculations of shortening orientations and magnitudes from depths to Moho and neotectonic movement magnitudes. From S. L. Yunga's data [*Grachev,* 2000].
1 – principal directions of calculation on the coordinate grid ($20' \times 30'$); 2 – auxiliary directions of calculation; 3 – nodal points to which the crustal thicknesses being calculated are tied; 4 – symbolic representation of relief along calculation directions; 5 – calculated directions of compression axes (P) and relative extension axes (T).

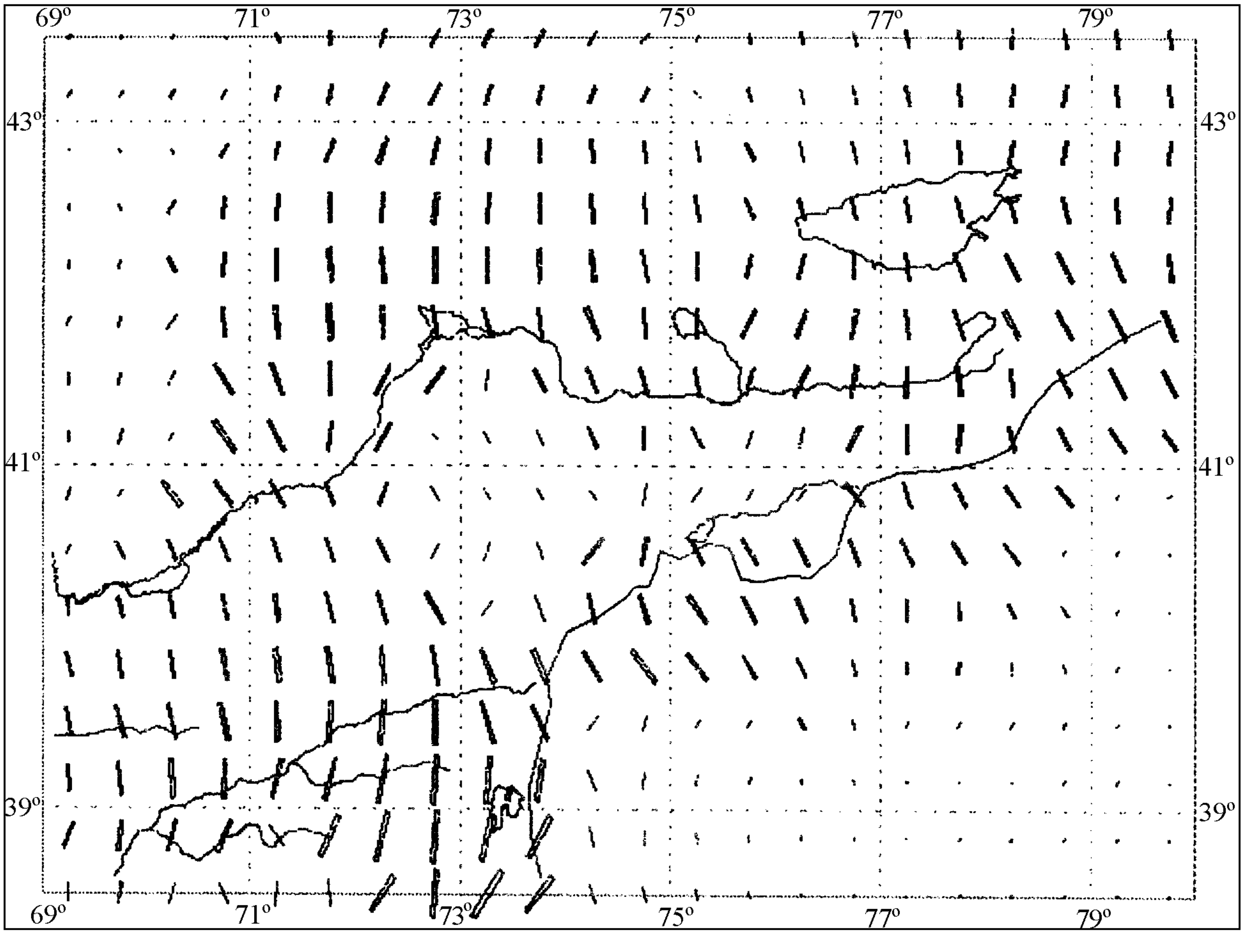

Figure 4. Orientations of main axes of compressional deformation, as determined from the Neotectonic Map of Northern Eurasia (From S. L. Yunga's data [*Grachev,* 2000]). Length of bars is proportionate to shortening amounts.

can be determined from incompressibility conditions:

$$E_z + K(E_1 + E_2) = 0; \ i.e., \ K = -E_z/(E_1 + E_2) \ .$$

Primarily, in the context of this approach, a uniform grid of geographic nodes was chosen in such a way as to cover the study region with a longitudinal spacing of 0.5° and latitudinal spacing of 0.33° [*Grachev,* 1997]. In the grid nodes, values of vertical neotectonic movements and depths to Moho are determined. The next calculation stage involved assessing the values E_1 and E_2. The last stage was to calculate shortening due to the increase in the vertical dimension of a unit volume. The calculations yielded assessments of orientations of the main shortening directions in the horizontal and the values of shortening proper (Figure 4).

Determining the Amount of Shortening that Leads to Deformation of Peneplanation Surfaces

Method 2 was employed in all four areas to assess shortening based on measurements of peneplanation surfaces bent in the course of deformation and offset by faults relative to their horizontal plane projections. Measurements were taken along profiles across the strike of neotectonic structures. Methodologically, the shortening evaluations proposed by us follow the works [*Billings,* 1960; *Chediya,* 1986] and take into account both folding and faulting deformations.

Measurements were taken on 5–15 km sections of the profiles and averaged for $20' \times 30'$ cells of the coordinate grid, which enabled us to compare evaluations obtained using both methods.

The method employs observations on the attitude of peneplanation surfaces that formed prior to the onset of the orogenic stage in the regional history. In Pamir and Tien Shan, orogeny spans an interval of ca. 20 m.y. from the Late Oligocene to Pleistocene inclusive [*Chediya,* 1986; *Shults,* 1948]. Over this period, the area of the present-day Tien Shan mountain edifice experienced uplifts and considerable subsidence events relative to its initial cratonic state, which persisted through the preceding period from the Triassic to the end of the Paleogene. Orogeny was accompanied by folding deformations that involved the basement surface (pene-

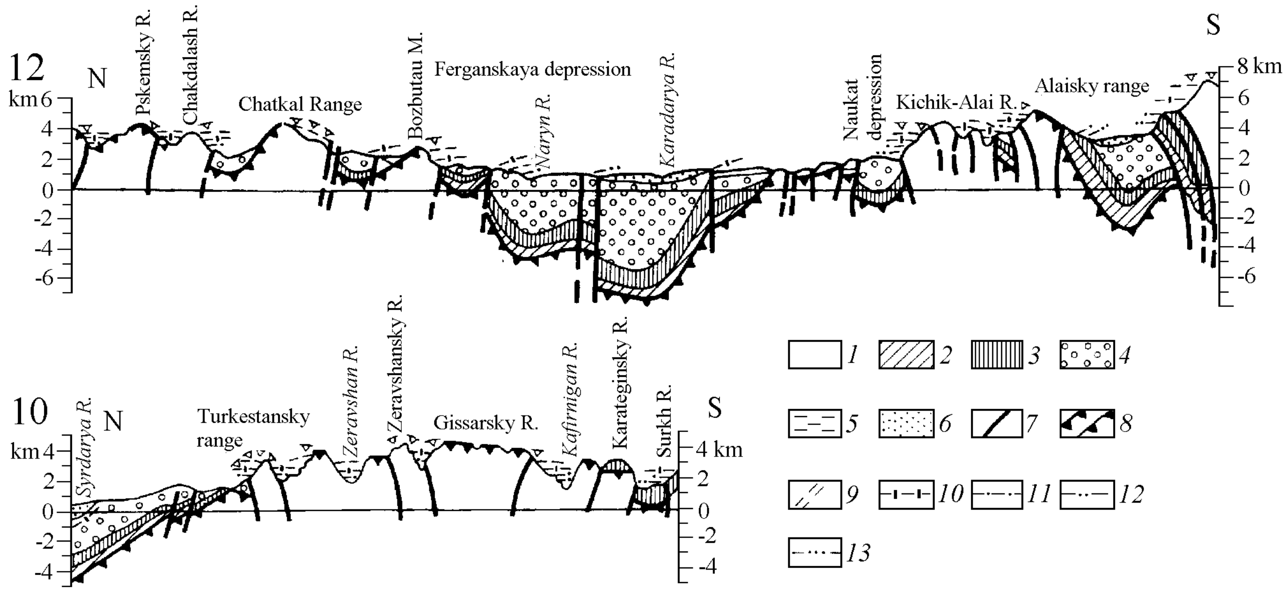

Figure 5. Structural profiles constructed by *Chediya* [1986]. Fivefold vertical exaggeration. 1 – pre-Mesozoic deposits undivided; 2 – Jurassic deposits; 3 – Cretaceous–Paleogene deposits; 4 – Cenozoic molasse; 5 – Middle Pleistocene deposits; 6 – Late Pleistocene to Holocene deposits; 7 – regional neotectonic faults; 8–13 – peneplained surfaces: 8 – pre-orogenic peneplain (initial peneplanation surface); syn-orogenic peneplanation surfaces (terraces, pediments) of different ages: 9 – Neogene, 10 – Early Pleistocene, 11 – Q_1, 12 – Q_2, and 13 – Q_3.

planation surface), post-Hercynian cratonic cover, and syn-orogenic sediments, as well as displacement of these surfaces along faults, chiefly thrusts.

Let us dwell on considerations favoring the idea of constancy of the length of peneplanation surfaces, on which this method is based. The length of these surfaces may, in principle, either increase (in anticline arches) or decrease (in syncline cores). Since both processes can be viewed as equally probable, over the section of a profile that crosses a syncline contiguous to an anticline such distortions may, by and large, intercompensate. Another consideration is that extension in anticline arches may lead to brittle deformations and pull-apart fractures. Such extension is hardly likely, because field observations would inevitably detect the appearance of numerous pull-apart fractures. On the other hand, significant (up to several tens of degrees) gradients of peneplanation surfaces, which are occasionally encountered, point to the possibility of palpable bending deformations [*Shults,* 1948], which should distort the original length of surfaces being measured. Therefore, as first approximation, the assumption of constancy of the length of surfaces being measured should be found reasonable.

To create the needed version of the method for determining the amount of shortening in Tien Shan and the Afghan–Tajik basin, it is especially vital to choose correctly the minimum size of a measurement object. This is because deformation can be realized within narrow spatial limits (in case of thrusts), while affecting two neighboring crustal blocks. From these considerations, the minimum block size was adopted at 20 km. Boundaries of measurement localities were drawn along faults (through the middle of a fault plane between the points of intersection of this plane with peneplanation surfaces) and through anticlinal or synclinal fold curves. The typical size of a block under study is a half wavelength (between anticline and syncline curves), and not a full wavelength between curves of the same type. To evaluate shortening, we measured the length of a locality first along the horizontal and then along the peneplanation surface in question. Ratio of these values yielded the shortening evaluation sought for. A profile was tied to a map with the grid of $20' \times 30'$ cells used in the study plotted on it. Within each cell like this, shortening values were averaged to account for the length of localities that fell in the cell. On average, every cell accommodated two or three measurement localities. The shortening of the profile was fully calculated from the sum total of its lengths, modern and reconstructed.

The most vital factor to the accuracy of shortening evaluations obtained by us is, needless to say, the concept of the structure adopted by the authors (and interpreters) of the profile. This applies primarily to the notions of fault angles and to how peneplanation surfaces are drawn beneath sediments in downfaulted blocks and "in the air," in upthrown blocks. In part, this also depended on the scale of the profile, the smaller scale always resulting in a greater degree of generalization of the structural pattern, which was bound to lead to understated shortening values compared to larger scale images of the same structure. On some, albeit rather infrequent, occasions, profiles did not run perpendicular to the structure, which resulted in somewhat understated evaluations. At the stage of averaging over cells, such an un-

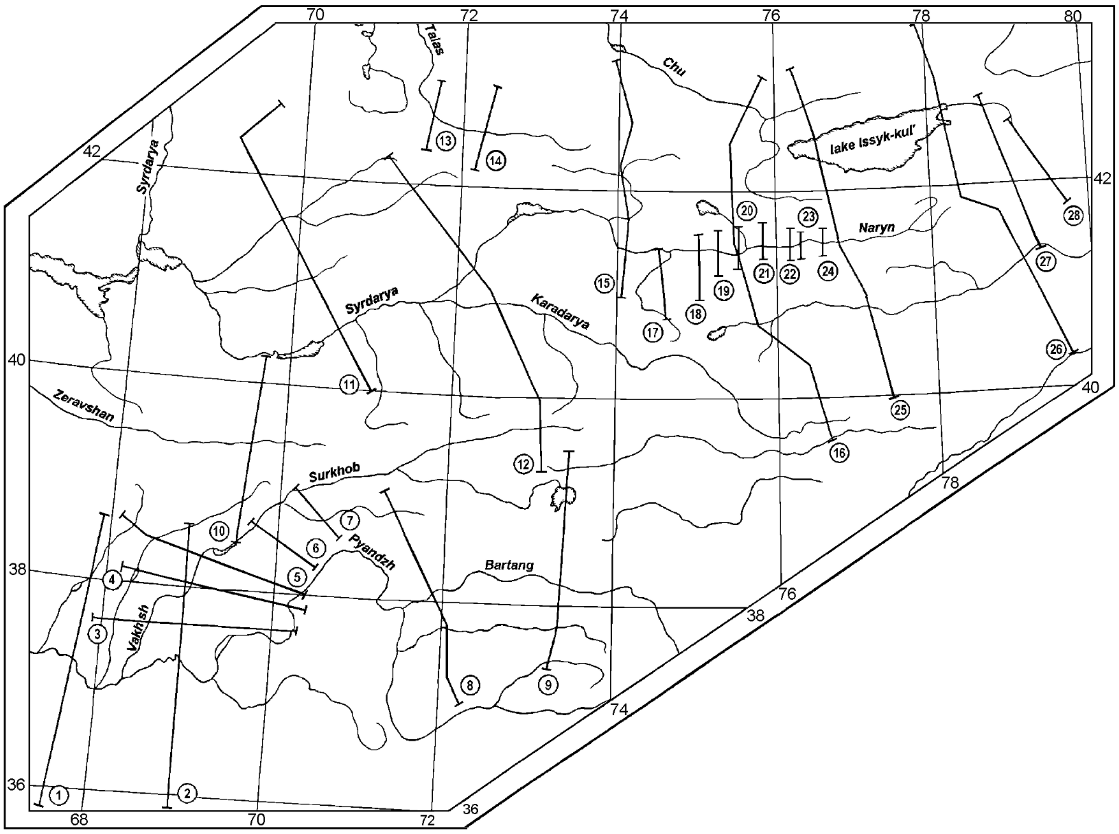

Figure 6. Location of measurement profiles across the Tien Shan, Afghan–Tajik basin, and Pamir structures.

derstatement was easily corrected using certain additional calculations. Eventual errors introduced by the measuring procedure itself are related to step-by-step measurements of distances using dividers. In all cases, this involves measuring not the perimeter length of a section, but the length of its chord. According to our evaluations, provided the profile does not have numerous sharp bends, this error does not exceed several hundredth fractions of the shortening value itself.

Input Material for and Results of Determining Crustal Shortening Across the Pamir–Tien Shan Region from Geomorphologic Data

To measure crustal shortening, we used geologic/geomorphologic cross-sections across the trend of neotectonic structures of Tien Shan and Pamir, on which deformed peneplanation surfaces and faults that offset them were plotted. The bulk of the acquired material is provided by transects (Figure 5) constructed by [*Chediya,* 1986], as well as by data for Tien Shan from [*Shults,* 1948] and [*Sadybakasov,* 1990], for the Afghan–Tajik basin from [*Bekker,* 1996], for Pamir from [*Chediya and Trofimov,* 1962], and by the N–S profiles across the Afghan–Tajik basin and the western part of the Fergana basin and northern Tien Shan constructed for this particular purpose by V. G. Nikolaev. Therefore, the data coverage embraces Pamir and the entire area of Tien Shan from the Tarim massif, Zaalaysky Range, and Afghan–Tajik basin in the south to the Chu–Ili basin in the north and from the vicinity of Tashkent in the west to the vicinity of Przhevalsk in the east (Figure 6). Twenty-eight profiles totaling ca. 5100 km were constructed, measurements were done on 427 localities, and shortening evaluations were averaged for 136 cells $20' \times 30'$ in size. The average shortening was found to be 17% (for Tien Shan, 11%, and for the Afghan–Tajik basin, 11% in the N–S and 49% in the E–W direction). Calculation results from particular profiles are listed in Table 1.

It is more rewarding to begin our consideration of results for the entire Tien Shan and Pamir region with outlining the main structural units. These are the three parts of the region with their distinctive structures, histories, and characters of neotectonic movements: Pamir proper, the Afghan–Tajik basin, and Tien Shan (northern and southern) [*Chediya,* 1986; *Makarov,* 1977; *Sadybakasov,* 1990; *Shults,* 1948].

Pamir as a whole displays extremely small crustal shortening values (0.05–0.15%). In contrast, for the Afghan–Tajik basin and Alay Valley, the greatest deformations reach 60%. For Tien Shan, evaluations from profiles range generally from 3–5% to 15% (Table 1).

The deformation pattern for northern and southern Tien Shan displays a marked increase in crustal shortening, up to 10–12%, in the central part, against 4–6% at the western and eastern peripheries of the mountain edifice. While con-

Table 1. Crustal shortening, total present-day length (km), and number of measurement localities for geomorphologic profiles under study through Tien Shan, Pamir, and the Afghan–Tajik basin (profile numbering, same as in Figure 7).

Profile number	Length, km	Number of localities	Shortening, %
1	323	12	6
2	286	17	16
3	229	25	36
4	209	26	42
5	205	20	50
6	76	10	59
7	60	9	58
8	273	41	<1
9	253	38	<1
10	197	9	4
11	317	20	3
12	369	22	13
13	70	13	12
14	88	14	9
15	263	12	12
16	429	16	9
17	62	7	16
18	64	10	7
19	43	6	11
20	50	7	8
21	44	7	18
22	33	5	16
23	13	5	26
24	40	7	18
25	404	18	6
26	421	17	6
27	169	20	5
28	109	14	4

sidering the areal pattern of crustal shortening values, one should note several local maxima of shortening, in the areas of the Talas (up to 12%) and Susamyr (up to 18%) basins and in the eastern (up to 25%) and western (up to 22%) parts of the Naryn basin. One can also discern a band in which deformation is increased (up to 10%) along the southern boundary of the Fergana basin and at the boundary of the Chu–Ili basin. These elevated shortening values are related to thrust structures developed at the basin boundaries.

The main direction of crustal shortening within Tien Shan, as established from the trend of principal ranges and valleys, is roughly N–S. Certain rather local changes in structural trends in Tien Shan are related to the northern part of the Talas–Fergana fault, which trends NW, and are typical of dextral shear. Shortening maxima in the Naryn basin are, most likely, due to its initial width decreasing eastward with a generally uniform N–S shortening. This shortening may be due to the northward movement of the Tarim massif. Therefore, at a qualitative level, from the totality of evidence the distribution pattern of crustal shortening values in Tien Shan is easiest to explain by pressure exerted by the Pamir high and Tarim massif.

Overall, axes of shortening in the crustal deformation field in the vicinity of the Afghan–Tajik basin and Alay Valley point consistently perpendicular to the Pamir high and across the strike of the southern boundary of Tien Shan. Characteristically, in a N–S direction, deformation increases locally rather sharply at the boundary of the Afghan–Tajik basin and Gissar Range (up to 15% to 65% over individual sections of Profiles 1 and 2), while the Afghan–Tajik basin itself shortens insignificantly in the same direction. Generally, the N–S shortening increases eastward from 6% to 16%. The EW shortening proper increases clearly toward the Alay Valley (from 36% in Prolfile 3 to 58% in Profile 7), with the trend of fold axes changing from N–S to NE–SW. In the south part of Profile 12, shortening values obtained from O. K. Chediya's material equal 48%, which is, by and large, in good agreement with the assessments based on A. Ya. Bekker's data. However, not inconceivably, the Alay Valley might accommodate major overthrusts that cannot be detected by geological methods, and, in reality, crustal shortening there might be considerably greater.

An important aspect of the study of deformation in the Alay Valley is to establish the type of deformation/stress state. Two extreme options should be distinguished: a thrusting environment (vertical position of the maximum extension axis) and a shear environment (horizontal position of the maximum extension axis). In this respect, studying structural cross-sections alone cannot yield material reliable enough. Data obtained by [*Korchemagin et al.,* 2000] from a study of shear joints (spatial orientation of joint planes and displacement marks on joint limbs) in Alay Valley structures revealed a considerable elongation of structures along the trend of the Alay Valley. According to these data, in palinspastic reconstructions Profiles 6 and 7 should be shifted perceptibly to the east of their present-day position. These data favor the model of a secondary nature of the bend of the Pamir arc [*Burtman,* 1999, 2000].

As mentioned above, in the Pamir high deformation is virtually absent, the N–S shortening recorded along profiles constituting tenth or hundredth fractions of a percent (0.05–0.15%). However, the character of deformation in the Cenozoic basins further north and west is suggestive of considerable changes in the orientation and mutual arrangement of parts of the Pamir structure at the neotectonic stage. In the light of N–S shortening values obtained by us, this can be interpreted as evidence of considerable shear deformations developing along the main faults within the Pamir high. Since the currently available material does not afford assessing the scale of such possible movements, it should only be stated that this hypothesis requires further refinement and testing.

Another problem emerging from the consideration of the same material refers to the behavior of basement of the Afghan–Tajik basin and Alay Valley. Two extreme cases are possible here: (1) detachments along the base of sedimentary cover while basement remains undeformed and (2) joint horizontal shortening of the basement and cover. The character of transition from the Afghan–Tajik basin to the Pamir high agrees less well with the first option, since no perceptible overthrusting is recorded there [*Bekker,* 1996]. The

Table 2. Comparison of shortening values for the Afghan–Tajik basin, obtained by (1) F. L. Yakovlev [*Grachev,* 2000] and (2) *Burtman* [1999]

Profile number	3		4		5		6		7	
	1	2	1	2	1	2	1	2	1	2
Crustal shortening	37%	33%	42%	40%	50%	51%	59%	59%	58%	–

existing concepts [*Kulagina et al.,* 1974; *Legler and Przhiyalgovskaya,* 1979; *Lukk and Vinnik,* 1975; *Trifonov,* 1979] of thrust duplication of the crust as the underlying cause of the nearly twofold crustal thickness in Pamir are not quite relevant, either, since the possible displacement magnitudes (proportionate to shortening – i.e., smaller in the south and greater in the north of the basin) cannot account for the rather uniform crustal thickness beneath the entire Pamir. In the context of the second option, it remains unclear, how deep into the mantle the roughly twofold horizontal crustal shortening might reach, and how geometrical parameters of the medium (directions and magnitudes of displacement of volumes) change with depth. It must be stated that this issue cannot be resolved with confidence as yet.

Our assessments of crustal shortening [*Grachev,* 2000] are in good agreement with the previous results [*Burtman,* 1999] (Table 2).

Comparison of our results with shortening assessments obtained by the other workers from Tien Shan and Pamir using various methods (Table 3) reveals a fundamental similarity of the values (from Method 2) to those of O. K. Chediya, who used the same peneplanation surfaces in his study, and a close match of assessments from the Method 1 and data based on the crustal thickening model [*Avouac et al.,* 1993].

Comparing Results from Tien Shan and Collating the Two Mountain Building Models

Comparison of data obtained from Tien Shan using Methods 1 and 2 revealed an overall similarity of results both in terms of orientation of maximum shortening axes and localization of major shortening maxima (Figure 7). A good match is also shown by the general patterns of crustal shortening increasing from the western and eastern peripheries to the 74°W meridian, central to Tien Shan. The correlation coefficient for seven values of total shortening that coincide on meridians is 0.87 (Figure 8). Such a correlation, in our opinion, suggests that assessments obtained from nonuniform input data point to a high degree of similarity of the models used. This supports the idea of a direct relation between crustal thickening in Tien Shan and N–S crustal shortening. Note that, generally, for other regions one cannot expect such a coincidence of possible assessments, because great shortening values in the Afghan–Tajik basin are, more often than not, accompanied by crustal attenuation, and, conversely, an almost total lack of shortening in Pamir is associated with the greatest crustal thicknesses (Figure 8A). This implies that mountain building in areas adjacent to Tien Shan is related not to horizontal compression (shortening) of the crust, but to some other process.

The direct correlation of thickening and orogenic shortening of the crust, established for Tien Shan, enables us to assess the possible contribution to orogeny from the other process, which was discussed at the beginning of this paper. The point is that the regression line for 0% shortening from peneplanation surface deformation data falls on ca. 12% shortening from crustal thickening data. This might mean a contribution to crustal thickening in Tien Shan from the other mechanism, underplating. This holds true at least for northern Tien Shan east of the Talas–Fergana fault, where, beginning in the Paleogene, manifestations of a volcanism characteristic of mantle plumes are recorded [*Grachev,* 1999; *Sobel and Arnaud,* 2000].

To assess the influence of this mechanism, we averaged Moho depths over the same N–S transects. The values obtained were plotted on a diagram (Figure 9). The regression line passing through these eight points and the initial 40-km Moho depth yields a depth of ca. 47 km at 12% crustal shortening (from Method 1). Since this shortening value corresponds to 0% shortening from bends of peneplanation surfaces, it can be deemed that, as a first approximation, the ca. 7-km crustal thickening is ensured by precisely this process, crustal underplating.

From the available data, we can roughly determine the qualitative relation between these two processes, which, as we have established, are responsible for crustal thickening, and, hence, mountain building in Tien Shan. For this purpose, let us find the average crustal shortening using Method 1 and shortening for the existing transects using Method 2. These values are, respectively, 19% and 8%. Because crustal thickening is accounted for by the first value (i.e., it is a joint effect of the two processes), while the second corresponds to shortening proper, the contribution from shortening is 0.43 (8% divided by 19%) – i.e., just below one half.

Mongolia, Sayan, and Altay

To characterize the deformation state of the area of Mongolia, Altay, and Sayan, geomorphologic profiles constructed by E. V. Devyatkin along seven transects [*Grachev,* 2000] were used (Figure 10). To determine the amount of deformation, we used measurements of gradients of peneplanation surfaces and displacements along normal faults and thrusts (Figure 11). This material, in terms of its reliability and eventual errors of shortening measurements, displays a number of peculiarities. Positions of peneplanation surfaces are

Table 3. Comparison of N–S crustal shortening evaluations in Tien Shan and the Afghan–Tajik basin by various researchers. After [*Grachev*, 2000].

	Longitude (from 68° to 96° E)																		
Researcher	68°	69°	70°	71°	72°	73°	74°	75°	76°	77°	78°	79°	80°	81°	84°	85°	86°	93°	96°
S. Yunga (this study)	–	12% STS	15%	21%	24%	23%	25%	18%	17%	19%	18%	16%	14%	–	–	–	–	–	–
F. Yakovlev (this study)	–	–	4%	–	–	12%	12%	–	9%	6%	6%	4%	–	–	–	< −1%	–	–	–
Same, locally	6% ATD, merid.	17% ATD, merid.	–	–	10% TL	–	–	–	20% NRN	–	–	–	–	–					
[*Chediya*, 1986]	–	–	7%	5%	–	5%	–	–	4%	–	–	6%	–	–	–	–	–	–	–
Same, locally	–	–	–	–	11% CHA	30% ALV	11% NAN	–	–	–	–	–	–	–					
[*Avouac, Tapponnier et al.*, 1993]	–	–	–	–	–	–	–	–	19% 23% 37%	–	–	–	–	–	–	11% 30%	–	–	0%
Same, in km									96 km	–	107 km	–		74 km	54 km	66 km	38 km	17 km	–

ATD = Afghan–Tajik basin; STS = southern Tien Shan; TL = Talas Alatau and Kirghiz Alatau; CHA = vicinity of Chatkal basin; NAN = Nanai basin; NRN = Naryn basin; ALV = Alay Valley.

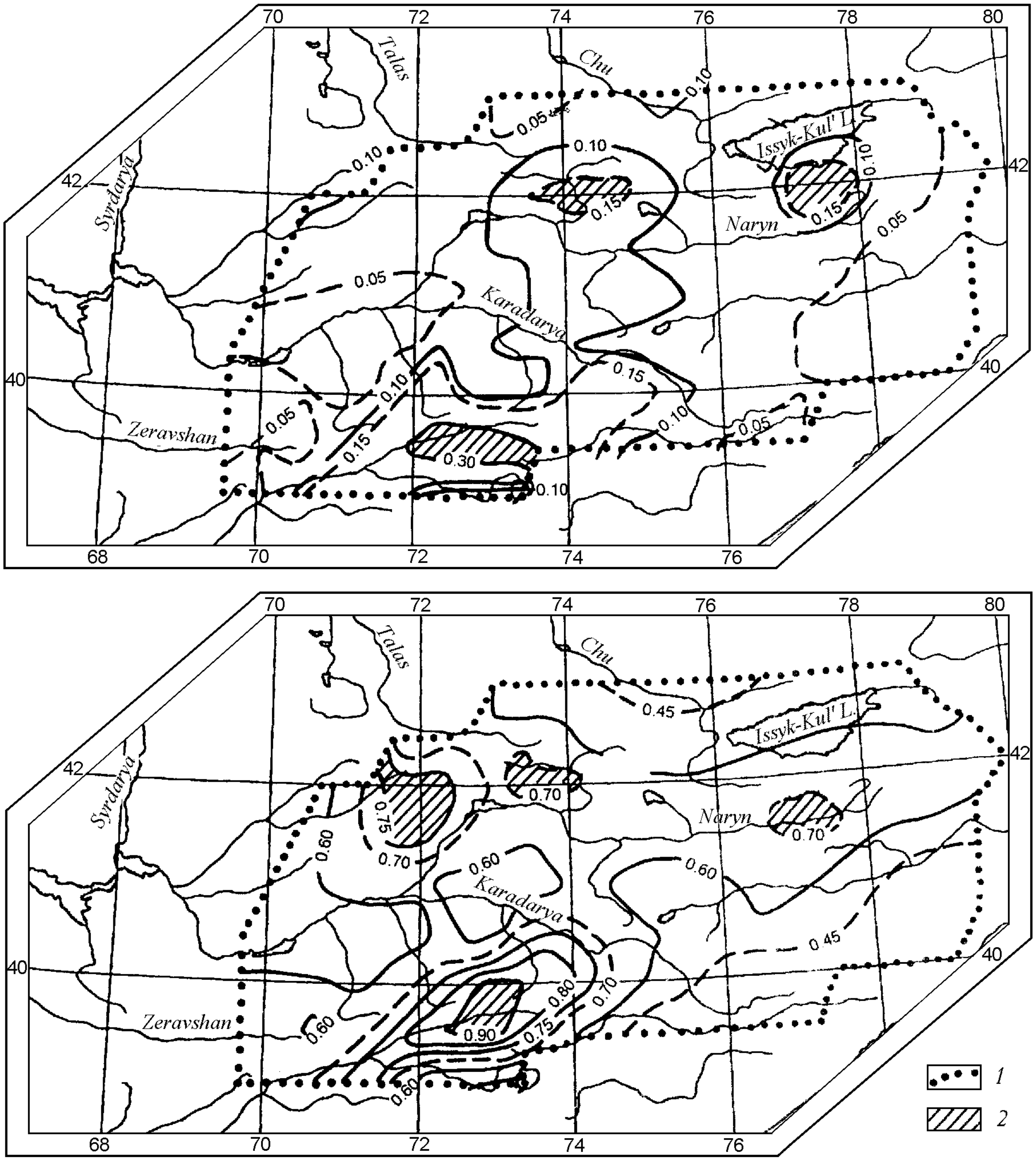

Figure 7. Areal distribution of crustal shortening values for Tien Shan, normalized from 0 to 1 for each data set [*Grachev,* 2000]. Top, shortening from peneplanation surfaces (F. L. Yakovlev) and bottom, shortening from crustal thickening (S. L. Yunga). 1 – boundary of data sets under comparison, 2 – local deformation maxima.

plotted with the greatest degree or reliability on relatively flat watersheds and plain areas. In transition from tablelands to valleys that are downfaulted or depressed along thrusts, these surfaces are not preserved, and they had to be restored graphically. In this restoration, care was taken to preserve average gradients of the peneplanation surface characteristic of neighboring localities. Therefore, in most cases vertical displacements of peneplanation surfaces can be deemed relatively well known. Exact fault angles were known only in rare cases, where the faults (chiefly, Quaternary thrusts) had been drilled. Most frequently, fault angles had to be assesses from previous expertise, and we assumed

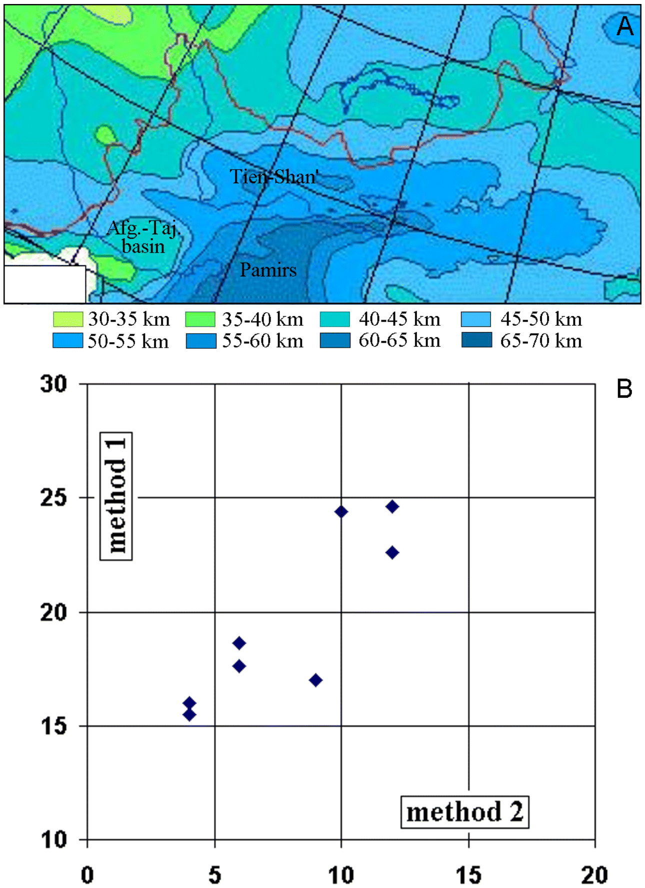

Figure 8. A – depths to Moho in the Pamir–Tien Shan region, after [*Grachev,* 2000], and B – comparison of shortening evaluations (percent) from Methods 1 and 2.

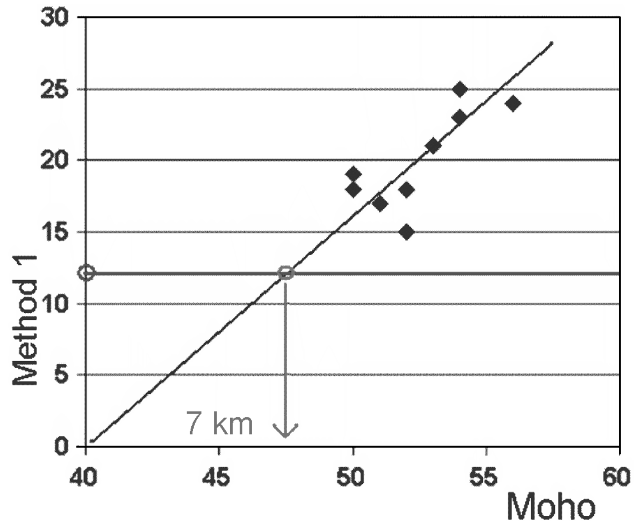

Figure 9. Comparison of shortening evaluations from N–S transects using Method 1 and averaged Moho depths from the same transects. Determination of crustal underplating.

normal faults to have angles of ca. 70°. Despite the seeming unreliability of a considerable proportion of the material, the amount of shortening itself was determined mainly from the average gradient of peneplanation surfaces, which usually equals fractions of a degree. Even over short spans, these gradients were only rarely as great as 1 to 5 degrees. As for the impact of faults, these contributed values of 2–3% over distances of 20–30 km (the $20' \times 30'$ coordinate grid) only occasionally. For this reason, only one profile yielded a shortening value of 1.2%, and the rest displayed extension of tenth fractions of a percent (Table 4).

A circumstance of importance to our study is that perceptible slip displacements were reported from this region (see, e.g., [*Solonenko and Florensov,* 1985]), which point to shortening of the structure in a NE direction and its extension in a NW direction. Needless to say, on profiles (i.e., in vertical sections) these displacements, as a rule, cannot be recorded, and, accordingly, they do not contribute to our assessments of shortening (extension). However, horizontal shortening/extension deformations do not, in principle, lead to crustal thickening (thinning), and, in this sense, they bear no implications to the main purpose of this study, determination of the role of crustal shortening in mountain building.

The relief of Mongolia, Altay, and Sayan over the portions under study is characterized by a range of elevations, from 500–1000 m in valleys and plains to 3–4 km in mountain edifices. Since the amounts of horizontal shortening obtained by us are extremely insignificant, they can, as a first approximation, be inferred to suggest no persistent relation between the amount of horizontal shortening (extension) and intensity of mountain building processes over the territory of Mongolia and southern Sayan Mts. This, therefore, rules out any impact from the collision of the Indostan and Eurasian lithospheric plates on neotectonic reactivation processes in this region. For this region, based on the data of A. F. Grachev and E. V. Devyatkin, one may hypothesize a genetically uniform mountain building process, likely related to rift or incipient rift settings [*Garchev,* 2000].

Table 4. Crustal shortening values from profiles in Mongolia and Altay

Profile	N–O	K–L	I–J	C–D	A–B	G–H	E–F
Present day length, meters	884000	520000	238000	556250	1275000	550000	284750
Shortening, % (“–” = extension)	–0,04%	–0,76%	–0,53%	1,21%	–0,19%	–0,08%	–1,31%

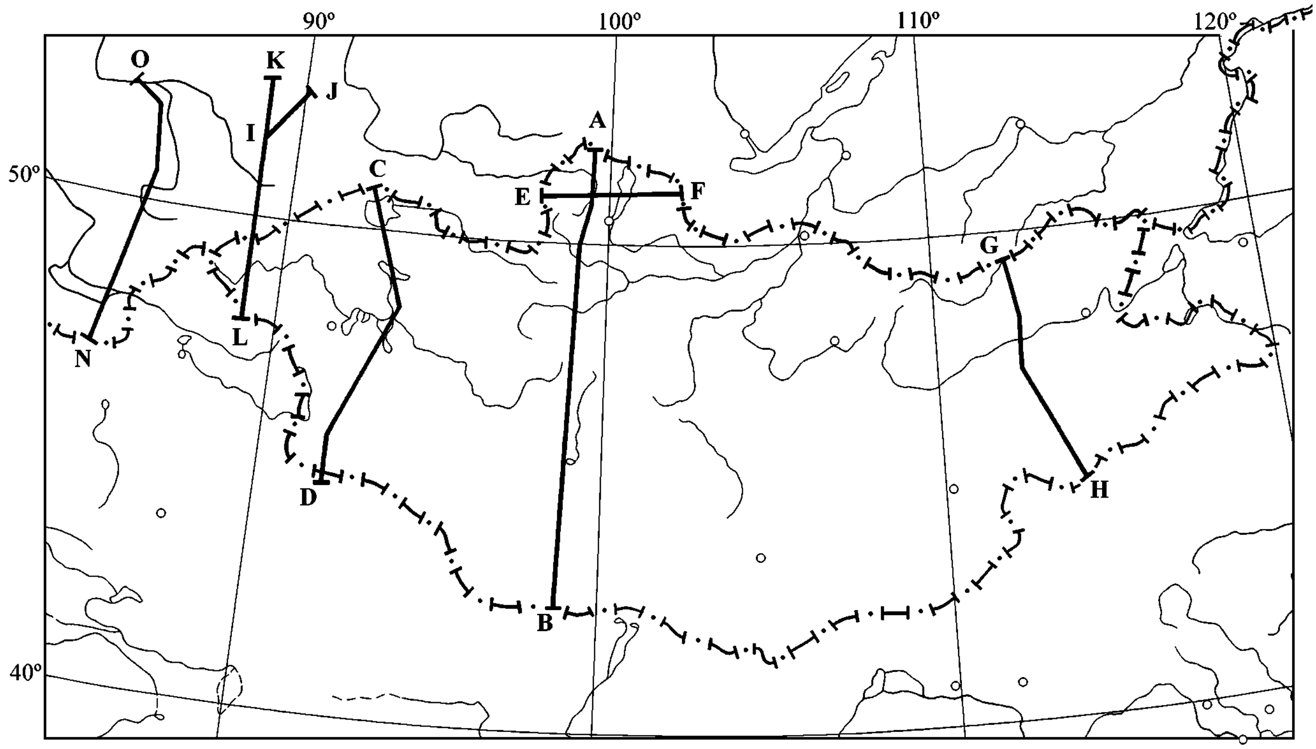

Figure 10. Location of profiles in Altay and Mongolia.

Discussion

Note first of all that crustal shortening assessments obtained by us from Tien Shan, the Afghan–Tajik basin, and Pamir, as well as the territory of Altay, Sayan, and Mongolia, refer to those deformations accumulated over the past 20 to 30 m.y. through the reactivation stage of mountain building processes. Assessments obtained from all the structures in point, except the Afghan–Tajik basin, are not meaningfully comparable to those crustal shortening evaluations that are usually performed using structural geological sections through major portions of fold-and-thrust belts, because folding and mountain building (in the strict sense) mechanisms are considerably dissimilar. This is readily demonstrable from data on considerable crustal shortening in the Afghan–Tajik basin. The basin itself exhibits no crustal thickening, and the notions of the crust subducting beneath Pamir are confronted with certain difficulties [*Bekker,* 1996] and are not shared by all the researchers. Since we can confidently attribute mountain building in Tien Shan to a combined effect of crustal shortening (and thickening) and underplating due to an impact from a mantle plume, deformations in the Afghan–Tajik basin, which are more likely to be accompanied by crustal destruction processes, and which clearly result from other mechanisms, should be classified as folding processes, whose nature is not discussed in this study.

Comparing our assessments of shortening with previous researchers' data reveals a reliable convergence of results from methods that employ the same type of input data. These are the data of [*Chediya,* 1986] for Tien Shan and of [*Burtman,* 1999] for the Afghan–Tajik basin, obtained from geomorphologic and structural transects, and of [*Avouac et al.,* 1993] for Tien Shan, acquired from crustal thickness measurements. Our explanation of the significant discrepancy in shortening assessments obtained by different methods draws on the assumption that shortening values obtained from deformations of peneplanation surfaces can be deemed true, as compared to shortening values calculated from the model of thickening of the crust during its shortening.

In principle, the conclusion on the presence of two crustal thickening mechanisms in Tien Shan is not at variance with the formation schemes for Tien Shan invoking pressure exerted by the Pamir high and Tarim block [*Avouac and Tapponnier,* 1993; *Bazhenov and Burtman,* 1986; *Cobbold and Davy,* 1988; *Kopp,* 1997; *Molnar and Tapponnier,* 1975; *Pozzi and Feinberg,* 1991; *Sadybakasov,* 1990], yet the crustal shortening value obtained by us, which ranges from 10 to 25–50 km from locality to locality, is considerably smaller than most other assessments. The assessed orogenic shortening of Tien Shan at the Pamir meridian [*Bazhenov,* 1993; *Bazhenov et al.,* 1993], based on paleomagnetic data suggesting 10° counterclockwise rotation of the Fergana–Alay block and a more conservative, compared to that of [*Burtman,* 1964], assessment of the magnitude of the Talas–Fergana shear, is 50–70 km and decreases westward, which can be viewed as a good fit of our data. Note in this connection the existence of theoretical evaluations of the width of the zone of impact from an actively moving continental plate on its neighboring

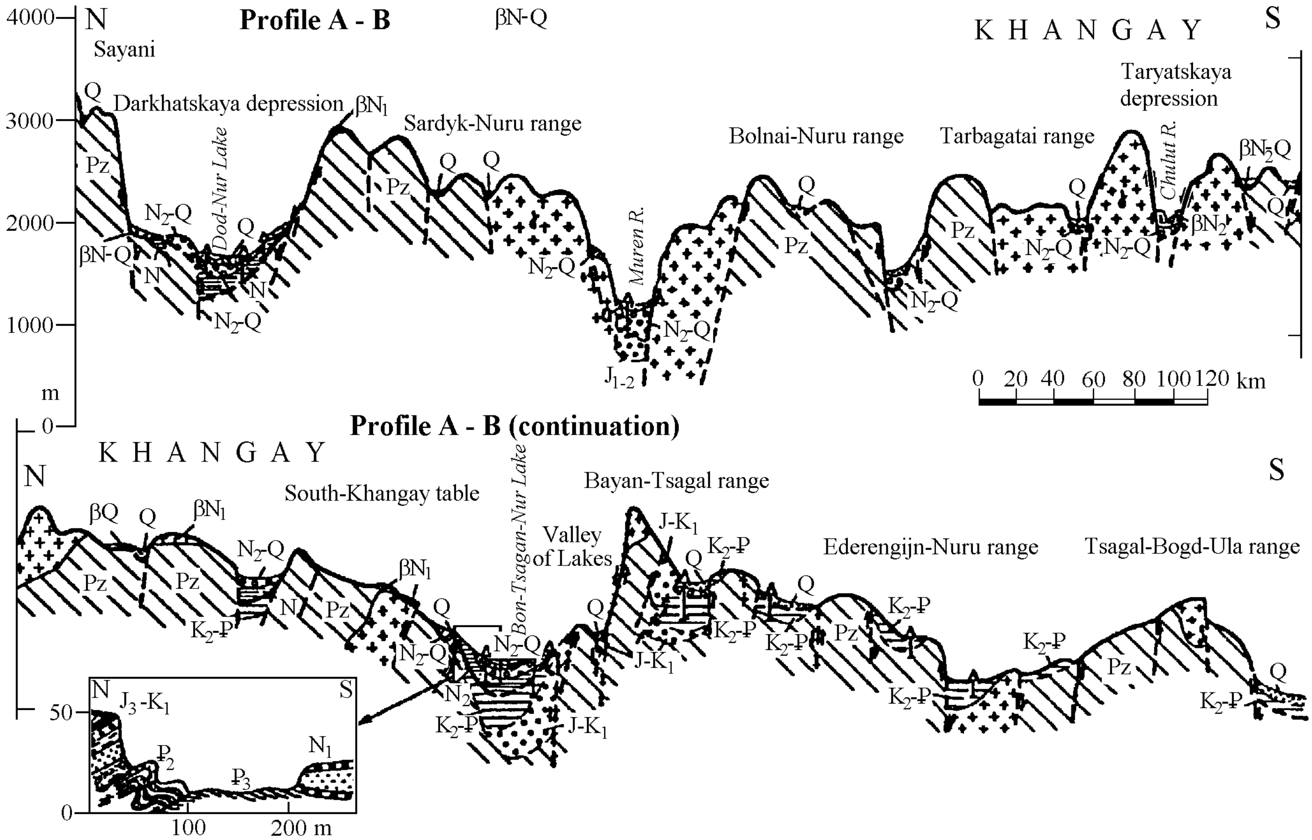

Figure 11. Geologic/geomorphologic profile through Mongolia, constructed by E. V. Devyatkin. After [*Grachev,* 2000].

less rigid lithospheric regions [*Bobrov and Trubitsyn,* 2000]. The width of such a zone coincides roughly with the lithospheric thickness (300 km), which, to a first approximation, corresponds to the entire width of Tien Shan (300–450 km). Therefore, our assessments of the width of the zone of impact of pressure exerted by Pamir and the Tarim block (300–400 km, the width of Tien Shan) coincide with the theoretically appraised width of the relief formation zone in front of a moving indentor continent, but it contradicts the majority of other schemes, which extend this impact onto other structures further north and east as far as Lake Baikal, e.g., [*Chen et al.,* 1993; *Halim et al.,* 1998]. As for the second mechanism, crustal underplating, it is in northern Tien Shan that a Cenozoic mantle plume, with 50–55 Ma magmatism, was shown to have existed [*Grachev,* 1999; *Sobel and Arnaud,* 2000], to whose impact the appearance of this mechanism can be attributed. Spatial and temporal relations of these two processes (mechanisms), as well as their cause-and-effect links, need to be elucidated as yet.

Much remains to be clarified regarding the nature of deformations in the Afghan–Tajik basin and Pamir. Undoubtedly, crustal shortening increases from southwest to northeast, and this takes place along flatly lying detachments in saliferous deposits of Jurassic age [*Belsky,* 1978; *Zakharov,* 1958, 1964]. Therefore, the behavior of crystalline basement under the detachment surface remains the crucial issue to the Afghan–Tajik basin. Some workers (e.g., [*Bekker,* 1996; *Burtman and Molnar,* 1993] propose subduction of basement beneath Pamir and Tien Shan. Our detailed assessments of shortening across the structures suggest that the deformation maximum occurred along the axis, and not flanks, of the basin, which implies a central position for the hypothesized underthrusting zone in basement and is in keeping with the modern models [*Burtman,* 2000]. This scheme, however, should lead to crustal thickening in the eastern part of the basin, which would show in maps depicting depth to Moho. Another possibility is uniform plastic shortening of basement, which, however, would imply destruction of the crust from underneath – i.e., migration of the Moho up the lithospheric section. Counterclockwise rotation of the boundary of the Afghan–Tajik basin and Pamir appears to be documented reliably enough by paleomagnetic data, facies analysis [*Bazhenov and Burtman,* 1990; *Burtman,* 2000; *Burtman and Gurary,* 1973; *Thomas et al.,* 1994, 1996], and geometrical analysis [*Bourgeois et al.,* 1997], and, consequently, the secondary nature of the Pamir arc can be considered a proven fact. However, our estimates of the magnitude of Cenozoic deformations point to a virtually total lack of N–S shortening in Pamir. It only remains for us to assume the existence of considerable amounts of slip on numerous faults roughly parallel to the Pamir arc, displacement of rigid basement blocks along them possibly resulting in the formation of this arc. In this case, the nature of increase in Moho depth to 70 km remains unclear, and one can merely ascertain that this discontinuity was forced to migrate down the lithospheric section. Therefore, the nature of internal deformation in Pamir and the Afghan–Tajik basin alike remains unknown, although, generally, the crucial impact of pressure exerted by the Indian subcontinent on the formation of the entire structure is beyond doubt.

Conclusions

1. It has been revealed that, in Tien Shan, pressure exerted by the Pamir and Tarim blocks leads to thickening of the earth's crust and horizontal shortening, but this impact is transmitted northward of the zone of contact of the blocks no further than the width of the mountain edifice, i.e. over a distance no greater than 300–400 km.

2. With respect to Tien Shan, mountain building can be interpreted as a combination of two simultaneous processes, horizontal shortening of the crust and its thickening due to underplating of new crustal material under the influence of a mantle plume. Contributions from these two processes to the total crustal thickening are approximately equal.

3. The most contrasting geodynamic settings are observed in the extensive area of junction between Pamir and Tien Shan. Considerable deformations in the Afghan–Tajik basin do not results in the amount of crustal thickening or regional uplift that would be proportionate to the amount of shortening, and the area remains, generally, least uplifted among the three neighboring ones. Conversely, uplifting of the Pamir high is due to the presence of the greatest thicknesses of the crust, but shortening deformations in it, as determined from deformations of peneplanation surfaces, are virtually absent. Therefore, in the context of the approach adopted by us, the natures of mountain building in these two areas appear to be dissimilar and, at the same time, open to discussion.

4. Crustal shortening data lend no direct support to the hypothesis of pressure being transmitted from the Indian subcontinent as far as the vicinity of Lake Baikal. Neotectonic movements in Mongolia are chiefly related to local, albeit common to the entire Baikal–Mongolia region, energy sources, associated with rifting processes.

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