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Scales of Horizontal Dislocations in Uralian Variscides and Early Kimmerides

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The issue of the establishment of the primary sedimentary surface in fold belts is directly related to reconstruction of the real geological history of a particular region. The most popular method of such reconstructions is based on compilation of geological cross sections with their subsequent straightening. Estimation of real values is always complicated by the incompleteness of material and the presence of fractures.

To estimate the scale of horizontal displacements in particular areas, we applied an original method based on some laterally sustained and unambiguous facies or paleotectonic boundaries.

In order to reconstruct areas of the initial accumulation surface of Upper Devonian–Lower Carboniferous sediments on the western slope of the Middle Urals (Fig. 1), we examined the walls of the Kama–Kinel system of troughs [1, 2], which are reliably traced based on reefal limestones of the Askyn Formation for the Frasnian Stage. Reefal microbial and algal limestones of the Storozhevsk Formation were used for the Famennian Stage. For Tournaisian sediments, thick-bedded and massive limestones were analyzed. Transitional zones between these section types are narrow. Therefore, their influence on the quantitative parameters is negligible [3, 4].

Subsequently, palinspastic reconstructions were performed in the following way: thrust sheets were back-tracked until the walls of different allochthons became juxtaposed and acquired the initial contours of the structure. In so doing, we assumed that rock masses moved during thrusting in the E–W direction orthogonally to the thrust front. In the case of sinistral shear displacements, they were assumed to be moving in the S–N or SE–NW directions. Owing to the coordination of walls, the model of the prethrust surface of the western Urals represents a paleotectonic (Frasnian–Tournaisian) map without regard for fold deformations (Fig. 1).

The reconstructed West Uralian fold zone comprises three large areas (Fig. 1). The most complicated tectonic structure is observed in the Vishera River basin, where thrusts are supplemented with strike-slip faults (particularly in the western part). Fracture planes show an eastward dip (from 20°–30° to 50°–60° or more). The shear component amounts to 35–40 km, and the horizontal displacement of allochthons ranges from 4.5 to 10 km. In the Kizel area, the leading role belongs to thrusts with eastward dipping planes (20°–50°). The horizontal displacement of allochthons varies from 3–10 km in general to approximately 10 km in reverse faults with the shear component up to 15 km. The Chusovaya River basin is crosscut by thrusts and reverse faults with the horizontal displacement amplitude of approximately 15 km and shear component of 15–20 km. Fracture planes have an eastward horizontal and gentle dip (5°–10°) in the west and a steep dip (40°–60°) in the east. The horizontal displacement of allochthons ranges from 5 to 10 km (40 km in some places). Some fractures are traceable through all three areas (Fig. 1).

The western thrusts gradually disappear in Lower Permian terrigenous sequences and are recorded only in single boreholes [5–7].

According to [8], straightening of folds increases the initial sedimentation area by 0.2–1.0 km in narrow sheets and by 2–3 km in the widest ones. These values are incomparable with horizontal displacements of blocks along thrusts. Therefore, the method of fold straightening is appropriate only for reconstructions at a scale of 1 : 100 000 and larger.

Folding and fracturing resulted in substantial (approximately 100–120 km) linear shortening of the primary sedimentation surface in the study area (Fig. 1).

Now, let us examine the younger formations developed on the western slope of the Urals and in adjacent areas of the Pre-Ural Foredeep (PUF). Here, analogues of the Upper Devonian–Lower Carboniferous sequences are represented by facies boundaries within the Middle–Upper Carboniferous and Lower Permian sequences. The boundary between the eastern margin

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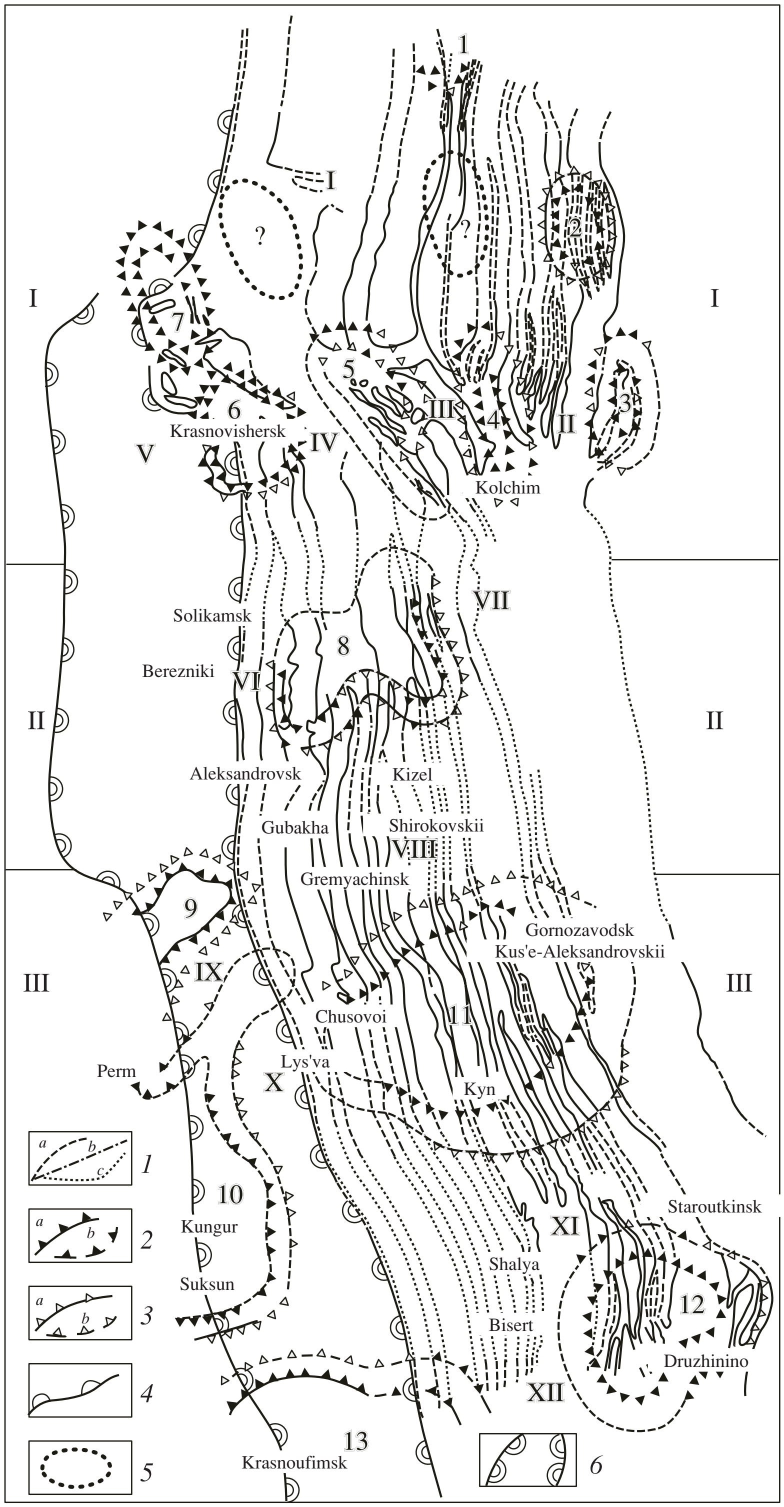

Fig. 1. Schematic palinspastic reconstruction of the Frasnian–Tournaisian tectonic plan. (*1*) Fractures: (*a*) proven, (*b*) assumed, (*c*) probable; (*2*) outer boundaries of walls of troughs: (*a*) proven, (*b*) probable; (*3*) inner boundaries of walls of troughs: (*a*) proven, (*b*) probable; (*5*) contours of probable Frasnian–Tournaisian uplifts; (*6*) boundaries of the PUF. Roman and Arabic numerals designate troughs and uplifts, respectively.

of the carbonate platform and terrigenous facies of the PUF established for different periods is most distinct. This boundary is readily recognized based on geological and geophysical methods. Moreover, it is exposed and accessible for the study. The boundary of the western wall of the PUF is emphasized by discrete or linear

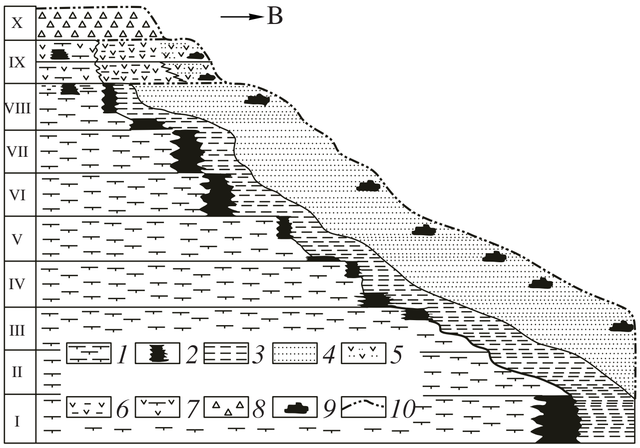

Fig. 2. Displacement of the eastern edge of the carbonate platform (western slope of the PUF) and its relation with terrigenous facies in the trough in the Middle Carboniferous–Permian [9]. (*1*) Bedded carbonate rocks; (*2*) organogenic buildups (OB) at the edge of the carbonate platform; (*3*) clayey–carbonate–siliceous pre-flysch formation; (*4*) sandy flysch; (*5*) substantially sandy sediments with evaporite lenses; (*6*) clayey rocks and evaporites; (*7*) carbonate rocks and evaporites; (*8*) red-colored molasses; (*9*) coastal OBs; (*10*) present-day erosional surface. Age scale: (I) Early Carboniferous–Serpukhovian Age; Middle Carboniferous: (II) Bashkirian Age, (III) Moscovian Age; Late Carboniferous: (IV) Kasimovian Age, (V) Gzhelian Age; Early Permian: (VI) Asselian Age, (VII) Sakmarian Age, (VIII) Artinskian Age, (IX) Kungurian Age; (X) Late Permian (Ufimian Age).

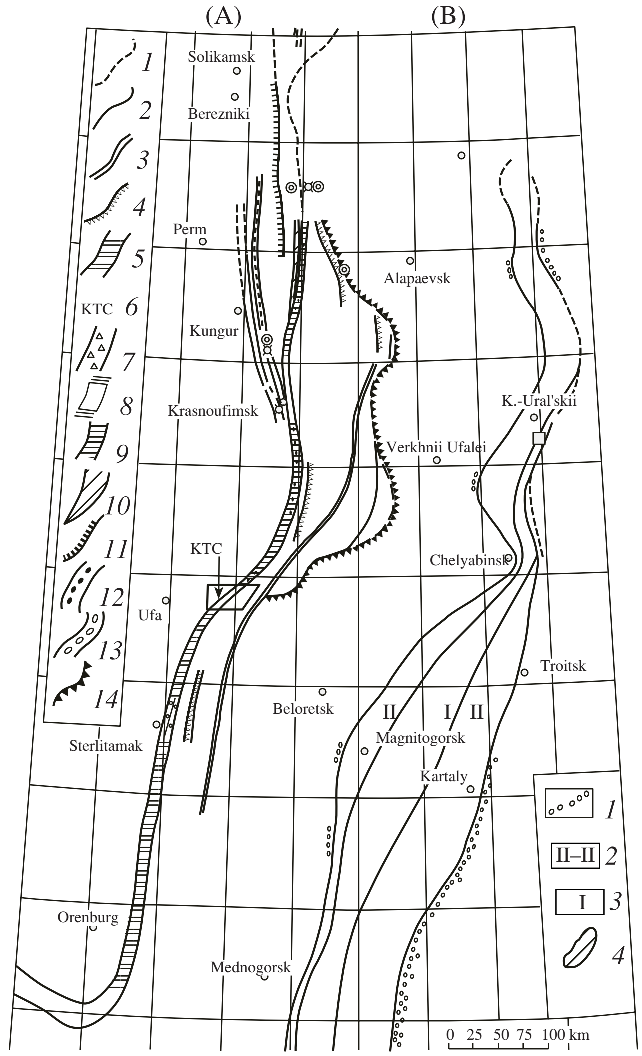

Fig. 3. Scale of horizontal displacements in the PUF (A) and on the eastern slope of the Urals (B) during the Late Paleozoic. Reconstruction was not carried out for the central part of the figure. (A) Scale of the westward displacement of the carbonate platform edge based on the boundary between the carbonate and terrigenous facies and OBs (Fig. 2). Eastern boundary of the field of carbonate rocks: (*1*) Lower Carboniferous; (*2*) Bashkirian Stage; (*3*) Moscovian Stage; (*4*) Upper Carboniferous; (*5*) Asselian–lower Sakmarian OBs; (*7*) OBs eroded in the Late Permian during the formation of the KTC; (*8*) buried Asselian OBs; (*9*) exposed Asselian OBs; (*10*) Sakmarian OBs; (*11*) early Artinskian OBs; (*12*) late Artinskian OBs; (*13*) early Kungurian OBs; (*14*) boundary of the Ufa Amphitheater. (B) (*1*) boundary of the field of Moscovian lagoonal and continental sediments; (*2*) marine sandy flysch (II–II); (*3*) marine carbonate and carbonate–terrigenous sediments of the Moscovian Stage; (*4*) areas eroded during the Moscovian Age.

organogenic buildups for virtually the entire Late Paleozoic (Figs. 2, 3A).

The PUF development is characterized by the well-known westward displacement of its entire structure owing to the movement of the thrust–fold front at the subsided eastern margin of the tectonic platform [9]. Tracing the temporal migration of the western edge of the PUF (Fig. 2, 3A) or, in other words, the boundary between the terrigenous and carbonate facies, we obtain concrete information on dislocations of this front. It appears that their scales are different for separate depressions of the PUF due to specific features of the structure of large interacting tectonic blocks (table).

One can easily see that the boundary between the foredeep and platform south of the Ufa latitude (Fig. 3A) is located in a western area as compared with its northern continuation and they are displaced along the Karatau tectonic complex (KTC). It should also be noted that reefal structures of different ages are split north of the KTC due to more rapid displacement of the western PUF wall north of the KTC as compared with the southern part of the PUF. This feature is responsible for the difference in displacement scales of the boundary between the western and southern parts of the PUF (table).

The obtained values reflect the scale of thrusting of the thrust–fold front over the edge of the East European Platform. This process was responsible for the westward displacement of the entire PUF structure.

On the eastern slope of the Urals, the shoreline of the Moscovian Sea was chosen as a readily recognizable boundary (Fig. 3B). This boundary is traceable

Scale of displacements on the western slope of the PUF

Geological time	Structure of the foredeep (trough)	
	Sylva	Bel'sk–Aktyubinsk
Bashkirian Age	>50 km	>15 km
Moscovian Age	37 km	10 km
Late Carboniferous	40 km	12 km
Asselian Age	35 km	10 km
Sakmarian Age	12 km	9 km
Artinskian Age	37 km	15 km
Total value	211 km	>70 km

owing to replacement of marine flyschoid sediments by red-colored sandstones (or conglomerates) and lagoonal clayey–sandy sediments with evaporites [10]. The reconstruction shows that the field of marine sediments is divided into two unequal parts. The wide (southern) part corresponds to the Magnitogorsk megastructure, whereas the significantly narrower (northern) part is located north of the Chelyabinsk latitude.

The Magnitogorsk megastructure, along with its Mugodzhary continuation, forms a monolithic tectonic block, where thrusting is less developed than in the northern area located between the Neiva and Rezha rivers and marked by significant horizontal displacements.

If we accept the width of the Moscovian Sea equal to 160 km within the Magnitogorsk megastructure as the almost unaltered primary value, shortening of the sedimentation surface of this sea north of the Chelyabinsk latitude was as much as 25–30 km, i.e., 5–6 times.

Thus, comparison of Figs. 3A and 3B reveals distinct correlation between structures of the eastern slope of the Urals north of Chelyabinsk and boundaries of the Ufa Amphitheater on the western slope. The massive block of the Ufa Amphitheater at the base of this structure served as an indenter standing in front of a large area of active horizontal displacements on the eastern slope of the Urals, where the displacements were several times higher as compared with similar movements in the Magnitogorsk megastructure.

Timing of the present-day PUF structure. Almost all tectonic phases proposed by H. Stille, except for the Variscian (Middle Carboniferous–Early Permian) ones, were defined in the Urals with a high degree of conditionality. The Variscian movements, which reflect periods of compression and folding, are confirmed by initiation and development of the PUF. It is usually believed that all dislocations are commonly related to this folding phase.

The continuous succession of sedimentation in the PUF up to the Triassic contradicts such an inference. Thrust dislocations involve all these sediments. In other words, thrust structures were probably developed after the Late Triassic. Since Jurassic and Cretaceous sediments in the Urals are developed locally and cannot be used for reliable paleotectonic analysis, some other indirect evidence should be used for this purpose.

Direct evidence. According to [11, 12], Triassic–Lower Jurassic rocks are subjected to thrusting in Triassic grabens on the eastern slope of the Urals [11, 12]. At the Chernyshev Ridge, dislocated Upper Permian redbeds are overlain with angular unconformity by horizontal Middle–Upper Jurassic marine sediments.

Indirect evidence. According to [12], Jurassic cleavage in rocks developed on the western slope of the Urals is traceable over all middle and southern areas of the Pre-Ural region. Hence, the most distinct thrusting phase in the PUF should be dated back to the Early Jurassic, which accords well with subsequent events in neighboring regions: spacious areas of the East European Platform, Barents Sea shelf, and the entire West Siberian Plate subsided in the Middle–Late Jurassic; i.e., the compression regime gave way to extension.

CONCLUSIONS

(1) We have obtained for the first time a quantitative estimate of the scale of horizontal displacements of facies boundaries (in response to the Variscian and Early Kimmerian phases of orogenesis) for the western and eastern slopes of the Urals. The Variscian orogeny in the central Urals produced a mountainous structure, the front of which was thrust onto the margin of the consolidated East European Platform. The rate and scale of this displacement are reflected in the PUF history. The maximal and minimal displacements of the western PUF boundary in the Sylva Depression are estimated at 211 and 70 km, respectively. In the Solikamsk time of the Kungurian Age, this movement stopped and the PUF was closed. This event marked termination of the Variscian orogenic episode of the alpinotype tectonics.

(2) The Sheshma time was marked by the onset of the Late Permian–Triassic stage of the mountain formation in response to the extension-mediated [13] graben–horst block (German-type) tectonics in the course of continuous sedimentation in the study area. Erosion products of the new generation of this orogenic structure were transported westward up to the Volga River [13].

(3) The Early Jurassic was marked by the formation of thrust and shear deformations. A belt of stress tectonics was formed on the entire western slope of the Urals. The scale of this process is reflected in the Late Devonian–Early Carboniferous structural plan. The primary sedimentation surface of this structure was shortened by 120 km. A similar shortening value is established for the eastern slope of the Urals based on paleogeographic reconstructions for the Middle Carboniferous.

(4) The Early Jurassic pulse was the last episode of the alpinotype tectonics. The Middle Jurassic was marked by the onset of a prolonged evolution of the Uralian mountainous structure in line with the German-type tectonics.

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