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BLIND DUPLEX STRUCTURE OF THE NORTH URALS THRUST BELT FRONT

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Abstract—New multichannel seismic-reflection profiles shot across the north Ural thrust front indicate the presence of previously unknown wedge-shaped foreland-verging blind duplex. The structure of this zone shows westward thrusting of the tectonic wedge of the Silurian–Artinskian assemblage into the foreland sedimentary cover. This process caused structural delamination of the basin succession, tilting of frontal molasse monocline above the leading edge of the low-taper allochthonous unit, thrust duplication and tectonic thickening of the wedge. Two distinct structural styles are recognized in the blind thrust. Its frontal zone formed by Artinskian shale has thin-skinned imbrication structure. The eastern internal zone consists of Silurian–Sakmarian carbonate-dominated sequences that have much more coherent thrust and fold deformations. This part of allochthonous unit forms a rigid "core" of the blind duplex. The structural geometry of the study area suggests its tectonic shortening of at least 60 km.

INTRODUCTION

During the last two decades, extensive petroleum exploration has taken place at the western flank of the Northern Urals, a vast frontier exploration area. The existence of 12–14 km thick sedimentary cover with proven reservoir and source rocks, and the proximity of the giant Vuktyl gas field intensified the investigation of geological structure of this region.

New seismic reflection profiles provide excellent subsurface images of thrust belt front and adjacent areas. Analysis of seismic data, coupled with surface geological and well information documented the presence of wedge-shaped blind duplex structures in the central part of the thrust front. The new structural model differs significantly from the previous ones, which suggest an overthrust relationship between the thrust belt and foreland basin. This paper outlines the structural geometry of this zone.

GEOLOGICAL SETTING

The area of interest is the central part of the north Urals thrust belt front, that extends for about 500 km from north to south along the western edge of the Pechora plate (Fig. 1). The belt is about 50–100 km wide. Structurally it

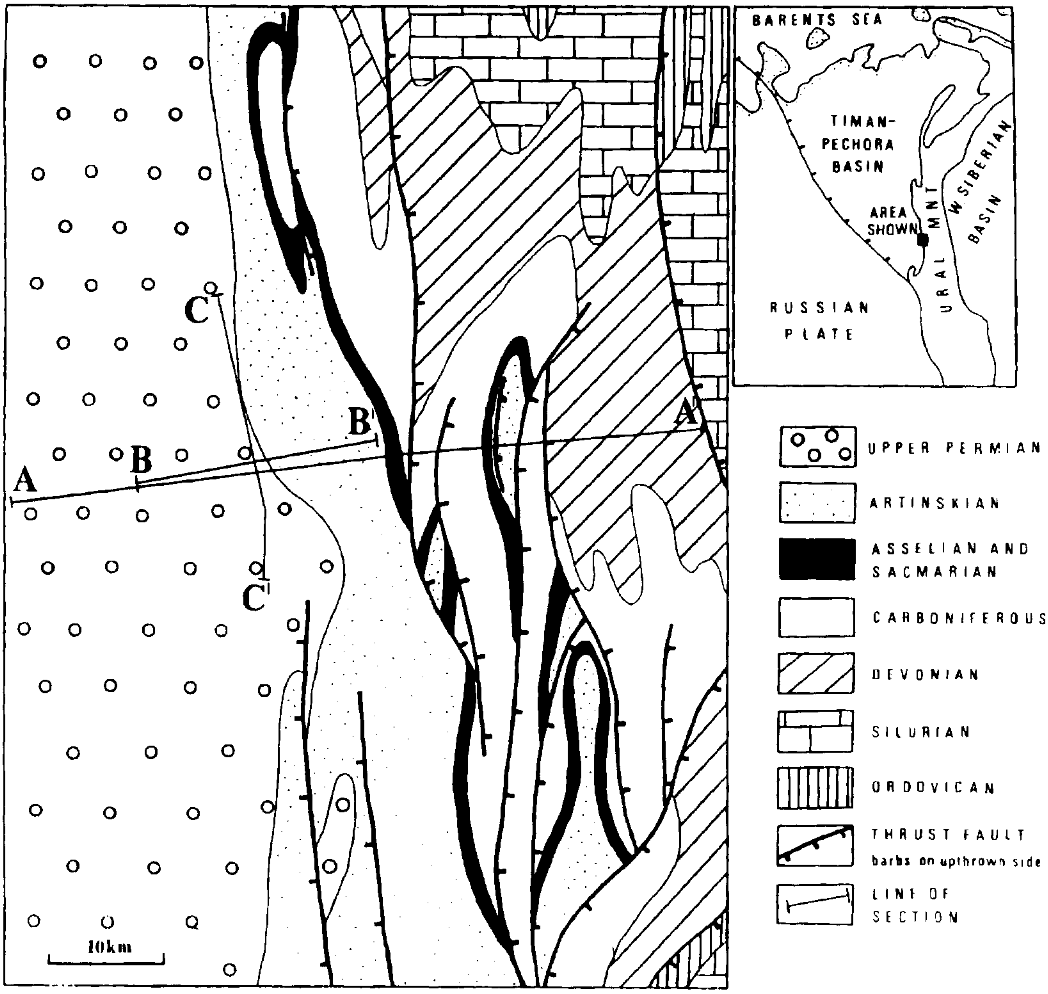

Fig. 1. Simplified geological map of the central part of the frontal zone of the north Urals thrust belt [after Udin (1983) with modifications] and regional setting of the study area, with locations of cross-section lines for Figs 2, 4 and 5.

represents a thick prism of sedimentary rocks, deposited on the margin of the Pechora plate, which have been detached from their basement and thrown into long parallel folds cut by thrust faults of large displacement (Fig. 2). Both folds and thrusts verge generally toward the adjacent stable plate (Kamaletdinov, 1974; Udin, 1983).

Stratigraphic data obtained from wells and outcrops are known for Ordovican to Permian strata. Most of the Paleozoic section of the study area, comprising Ordovican–Sakmarian deposits, consists of mainly massive, shallow-water carbonates interrupted by some shaly zones (Fig. 3). This typical passive–margine sequence reaches a maximum thickness of about 10 km. The upper part of sedimentary filling is represented by Artinskian to Upper Permian molasse wedge.

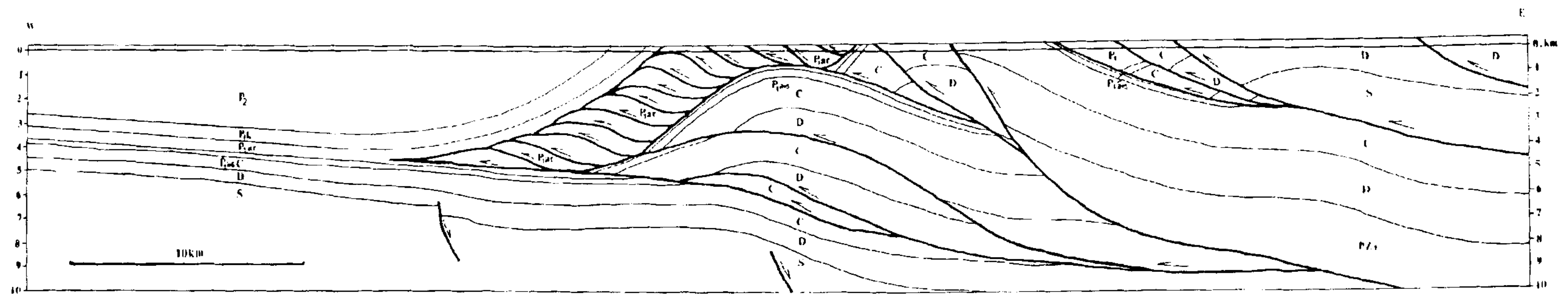

Fig. 2. W–E trending geological cross-section across the north Urals thrust belt (line A–A′ on Fig. 1). The cross-section is constructed from seismic and surface geology data.

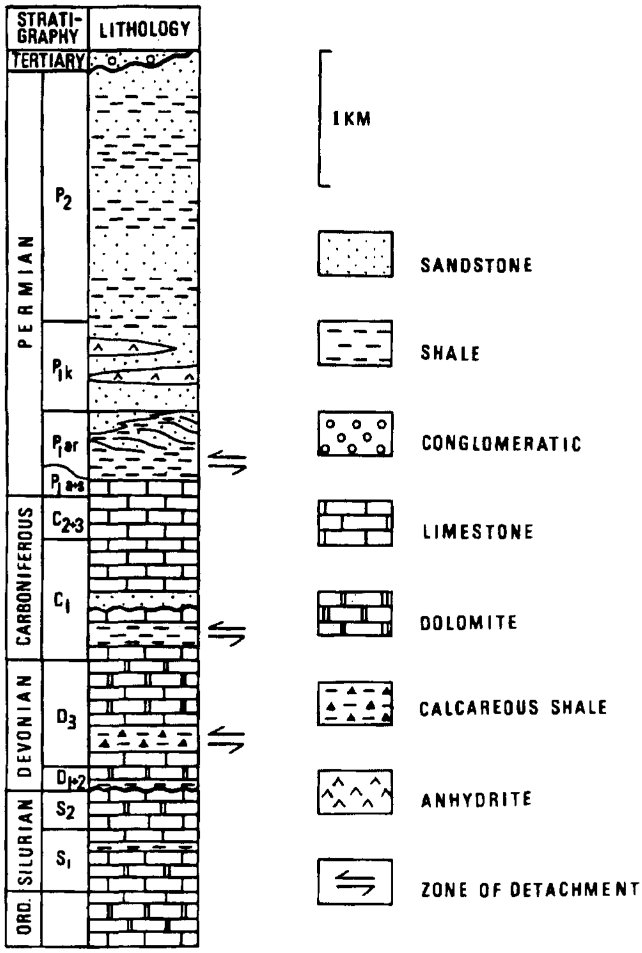

Fig. 3. Simplified stratigraphic column for the north Urals thrust belt front indicating detachment horizons.

There is a 200–300 m thick shale formation at the base of the upper sedimentary complex. These rocks crop out in a big part of the thrust front. Multiple repetitions of beds have been established in this area (Udin, 1983).

SEISMIC DATA

Petroleum-industry multichannel CDP seismic profiles were collected and processed by PGO Pechorageofizica in 1987–1990. They gave an unprecedented image of the subsurface structure of the western flank of the Northern Urals.

Figure 4 shows a typical west to east oriented seismic profile through the thrust belt front perpendicular to the general structural strike. It is clearly visible that the section towards the east becomes increasingly complicated, and the normal seismic sequence, inherited to the foreland basin, is easily divided eastward

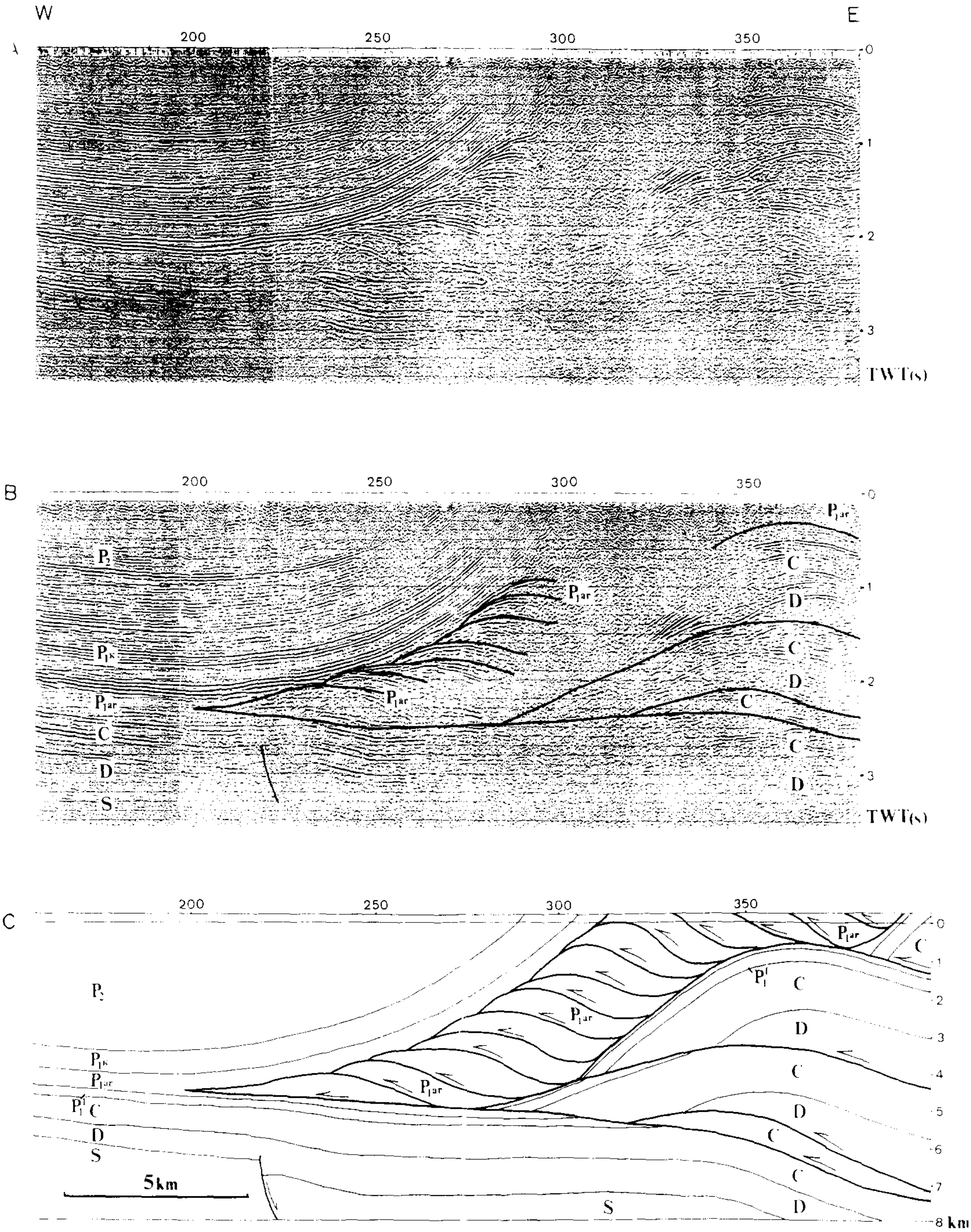

Fig. 4. Seismic expression of wedge-shaped blind thrusting [after Sobornov and Bushuev (1990) with modifications]. (A) Migrated seismic section of line B–B′: See Fig. 1 for line location. Scale on the right is a two-way travel time; (B) the same section with geological interpretation; (C) simplified geological section of the line B–B′.

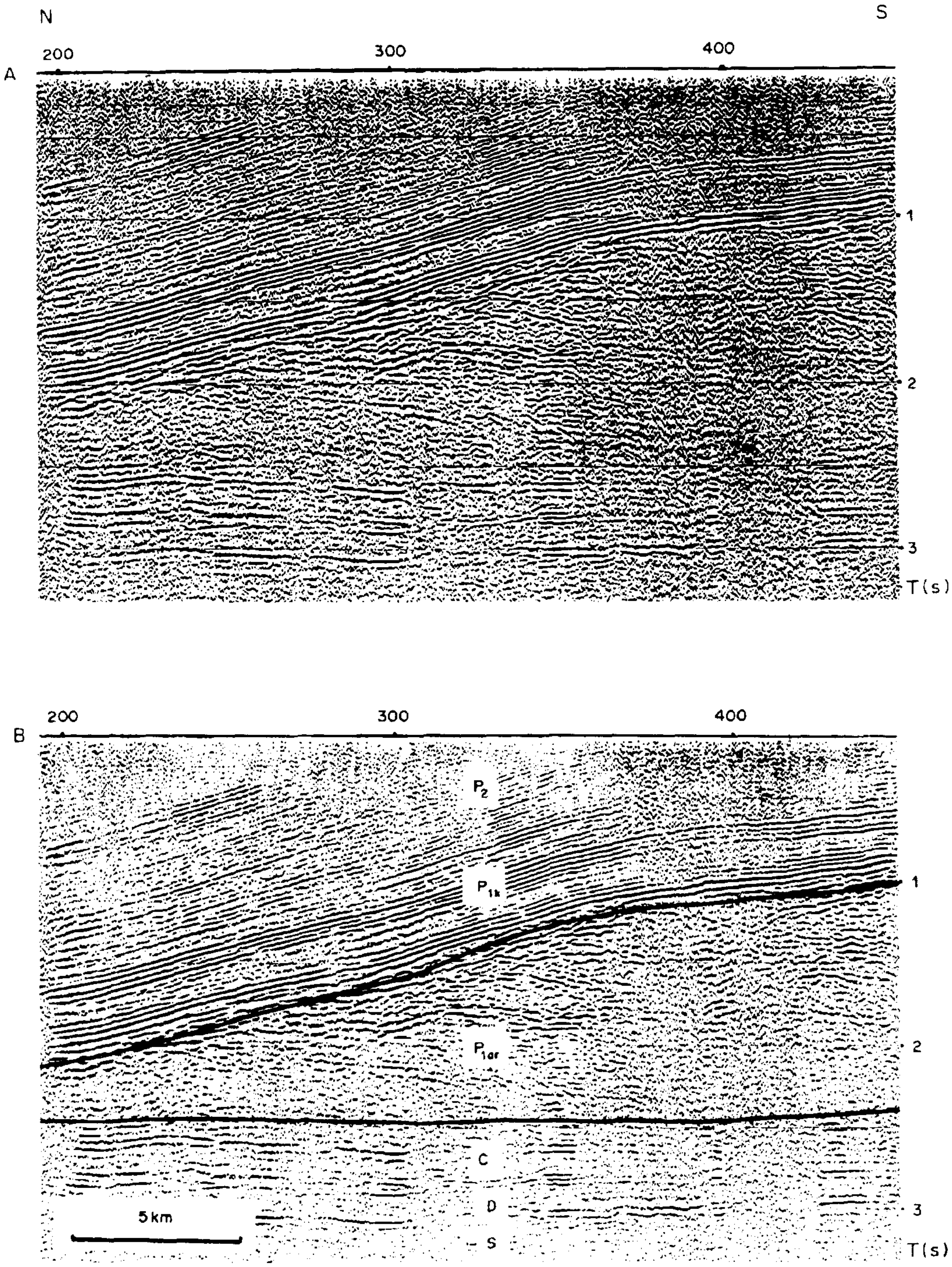

Fig. 5. Seismic expression of wedge-shaped blind thrusting [after Sobornov and Bushuev (1990) with modifications]. The section oriented along strike of the thrust front. (A) Seismic section of line C–C′: see Fig. 1 for line location. Scale at right is a two-way travel time; (B) the same section with geological interpretation.

into three packages. They are: upper and lower stratified packages and a wedge-shaped intruding middle package. The upper package is characterized by a series of strong, subparallel reflectors dipping westward. The lower one contains high-amplitude subhorizontal reflectors between 2.3–3.0 s TWT. In the western part of the section at 2.1–2.3 s TWT between the upper and the lower packages a transitional transparent zone is well defined. The middle zone is marked by generally short, curvilinear, discordant reflectors of varying amplitude. Within this package most reflectors dip westward.

Two distinct zones of similar reflection character are recognized in the middle wedge-shaped package: western and eastern. The western zone contains an abundance of discontinuous, curvilinear reflectors that dip mostly to the west from 0.8 to 2.2 s TWT. In the eastern zone high-amplitude, more continuous reflectors form a board antiform centered on the eastern edge of the section.

A seismic section extends from north to south along the strike of the thrust front is shown in Fig. 5. The general reflection image of this profile is the same, as discussed above. It should be noted that in this section the lower package is lying subhorizontally under deformed upper and middle ones.

STRUCTURAL INTERPRETATION

Geological identification of the seismic data was founded on the seismic stratigraphic methods, drill-hole information and surface geology. Together they provide a coherent picture of subsurface structure of the study area.

According to available data the upper package represents the Permian terrigenous shallow-water sequence, and the lower one corresponds to the Silurian–Lower Permian shelf deposits. The transparent transitional zone between the upper and the lower packages in the foredeep represents the Artinskian shale formation. Complicated internal reflection structure of the middle package suggests presence of a number of listric and flat-and-ramp faults and disharmonic folds. Structural discordance above and below the middle package, marked by convergence of reflections, shows its allochtonous origin. Seismic pattern of the study area shows that there is not any significant deformation ahead of the wedge-shaped body and shear zones above and below the allochton are kinematically linked.

Such structural pattern characterizes a wedge-shaped blind duplex or triangle zone recently recognized along the flanks of thrust belts all over the world (Bally *et al.*, unpublished data; Jones, 1982, 1987; Teal, 1983; Price, 1986; Banks and Warburton, 1986; Muller *et al.*, 1988 Koronovsky *et al.*, 1988; Sobornov, 1988, 1991; Sobornov and Buchuev, 1990; Stockmal and Waldron, 1990). According to this interpretation, an allochthonous unit can be viewed as a westernly tapering wedge that was formed between the lower and upper autochthonous levels. It was propagated westward, into the foreland basin by tectonic wedging. The result has been structural delamination of foreland filling, tilting of frontal monocline above the thrust tip, and thrust duplications of the allochthonous wedge. Parallelism of reflectors in the Permian molasse indicates that the process of blind subsurface thrusting was active during postpermian time. Equality of thickness of the middle package and height of the overlapping Permian monocline strongly supports this interpretation.

Two seismical zones distinguished within the wedge-shaped package correspond to different tectonic realms, which have individual compositions and structural styles. The eastern zone of the middle package consists of thick — up to 4 km relatively competent paleozoic sandstones and carbonates formed large-scale antiformal stack. The structure consists of fault-bounded located between low-angle thrust faults that form the floor and roof of the duplex. It represents a rigid "core" of the allochthonous unit. Approximately 4500 m of Silurian-carboniferous rocks have been penetrated before a major thrust fault was encountered in the bore-hole, located about 60 km to the north of the cross-section B–B′ in the crest of Sochinskaya anticline. Below the major thrust the Lower Permian carbonates were subsequently drilled.

The western zone displays a thin-skinned duplex formed by the Artinskian rocks. Displacement across individual thrust faults in this zone range from less than 10–1000 m. Such pervasive scaly structural style of deformation is visible in outcrops (Udin, 1983). Multiple repetition and anormous tectonic thickening of the Artinskian beds has been established in several bore-holes, situated in adjacent areas.

These two markedly different structural styles within the wedge-shaped allochthonous unit were probably controlled by physical properties of rocks it was formed by. The presence of a mechanically weak layer in the Artinskian shale facilited the development of thin-skinned deformation. The absence of such ductile layers in the competent Paleozoic carbonates resulted in its much more coherent thicker-skinned deformation during thrusting.

Palinspastic restoration based on estimation of tectonic thickening of the Artinskian shale in the thrust front reveals that at least 60 km of shortening have occurred in this area. This amount of shortening is equal to 300–500% increasing of normal thickness of the Artinskian formation along a 15–20 km wide zone of imbrication. This minimum displacement is much greater than it has previously been proposed and implies that much of the north Urals thrust belt is allochthonous.

STRUCTURAL EVOLUTION

The proposed structural evolution model of the thrust belt front is shown schematically in Fig. 6. It illustrates the kinematic development of thrust wedging. Basic structural style of deformation was controlled by detachment faulting (Jones, 1982, 1987; Price, 1986; Harrison and Bally, 1988). Major bedding-parallel detachment surfaces are situated at competency contrast zones in sedimentary cover — in the Artinskian shale and somewhere in the lower Paleozoic section.

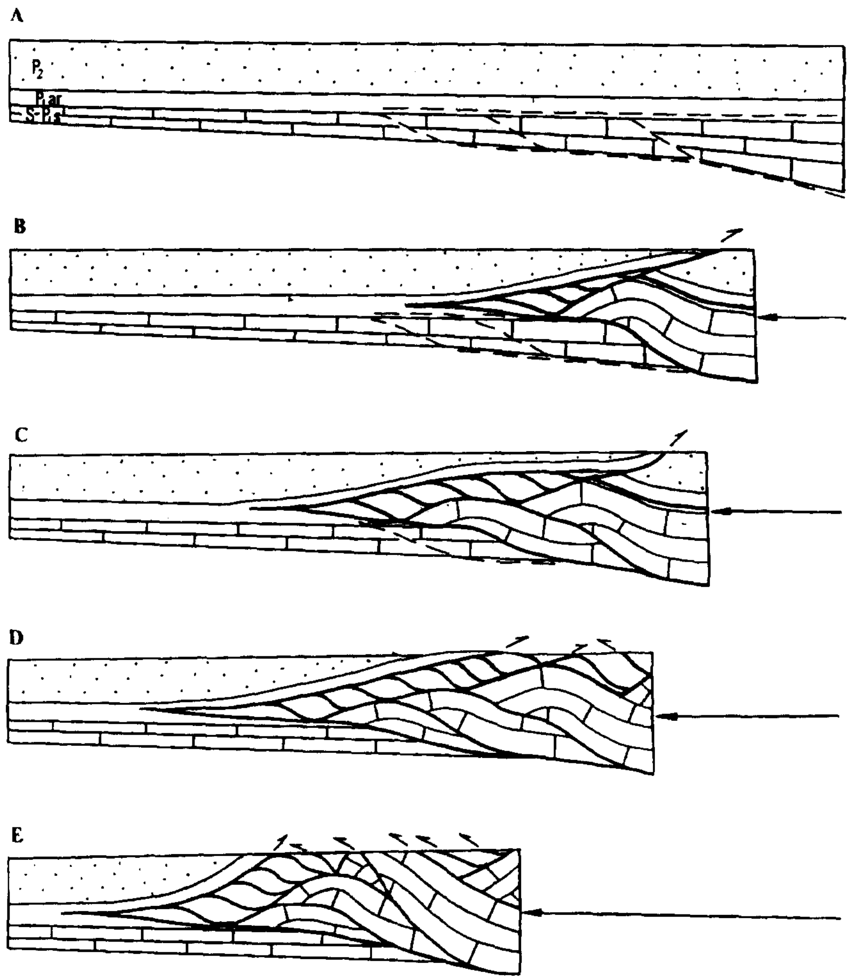

Fig. 6. Proposed model for structural evolution of frontal blind duplex. (A) Undisturbed section showing position of future thrust faults; (B–D) progressive stages of faulting and tectonic wedging. The antiformal stack generated between the upper and the lower detachments relatively migrates as its grows westward; (E) present structure of the thrust belt front. Length of arrows at right indicates amount of slip.

Deep-level thrusting began in the east. Propagation of thrust deformation nearer the surface was accommodated by foreland directed transport and duplication of the Paleozoic carbonate-dominated section and opposite-vergence hinterland-directed passive thrusting of molasse above upper detachment. Tectonic thickening of the wedge-shaped allochthon due to its imbrication caused the forming of steeply dipping monocline tilted away from the thrust belt.

There are at least two factors defined this way of structural evolution. They are: the relatively high density of Paleozoic carbonates, that forced the allochthonous wedge to “drown” in lighter molasse; and the presence of ductile Artinskian shale, where high-amplitude coherent deformation disappeared, because of its transformation into a number of small-scale thrust faults and folds. Perhaps these factors preserved the molasse section out of foreland-directed thrusting. Thin-skinned thrusting within the Artinskian shale in front of the wedge made an allochthonous leading edge smoother and maintained its low-taper profile.

Geometrical relationships in the blind duplex indicate east-to-west sequence of deformation. It explains a gradual eastward steepening and rotation of thrust faults. According to this model, continued compression produced a new sheet ahead of the wedge. A new anticline grew in front of the moving sheet, bounded above and below by originally planar or slightly inclined fault surfaces, which were favorable to thrusting (Dahlstrom, 1970; McGroder, 1989). Curvation of originally planar thrust surfaces during ramp folding caused increased friction in the roof and floor of the sheet. This process finally stopped propagation of the sheet. As a result, the next sheet was formed, again with a favorable fault plane orientation. Earlier and higher thrust sheets were consequently rotated and folded by growth of the underlying and younger ones.

CONCLUSIONS

Analysis of the recently collected data on fault and fold geometry indicates that the central part of the frontal zone of the north Urals thrust belt has a blind duplex structure. It was formed after the deposition of the Upper Permian molasse, which was involved in deformation. The horizontal compressive force during Urals orogeny in Late Permian-Mezozoic time caused the shortening of sedimentary cover for at least 60 km and development of the wedge-shaped allochthonous body intruded into the foreland basin filling near the base of the mollasse. Relatively competent Ordovican Sacmarian strata involved in tectonic wedging were shortened by duplication and formed of about a 4 km high antiformal stack. The stack consists of 3–4 folded thrust sheets. The less competent Artinskian strata were thrusted westward too, forming a thin-skinned "envelope" of wedge-shaped blind duplex. This structural model provides favorable conditions for petroleum accumulation in the antiformal stack below the Permian molasse monocline.

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