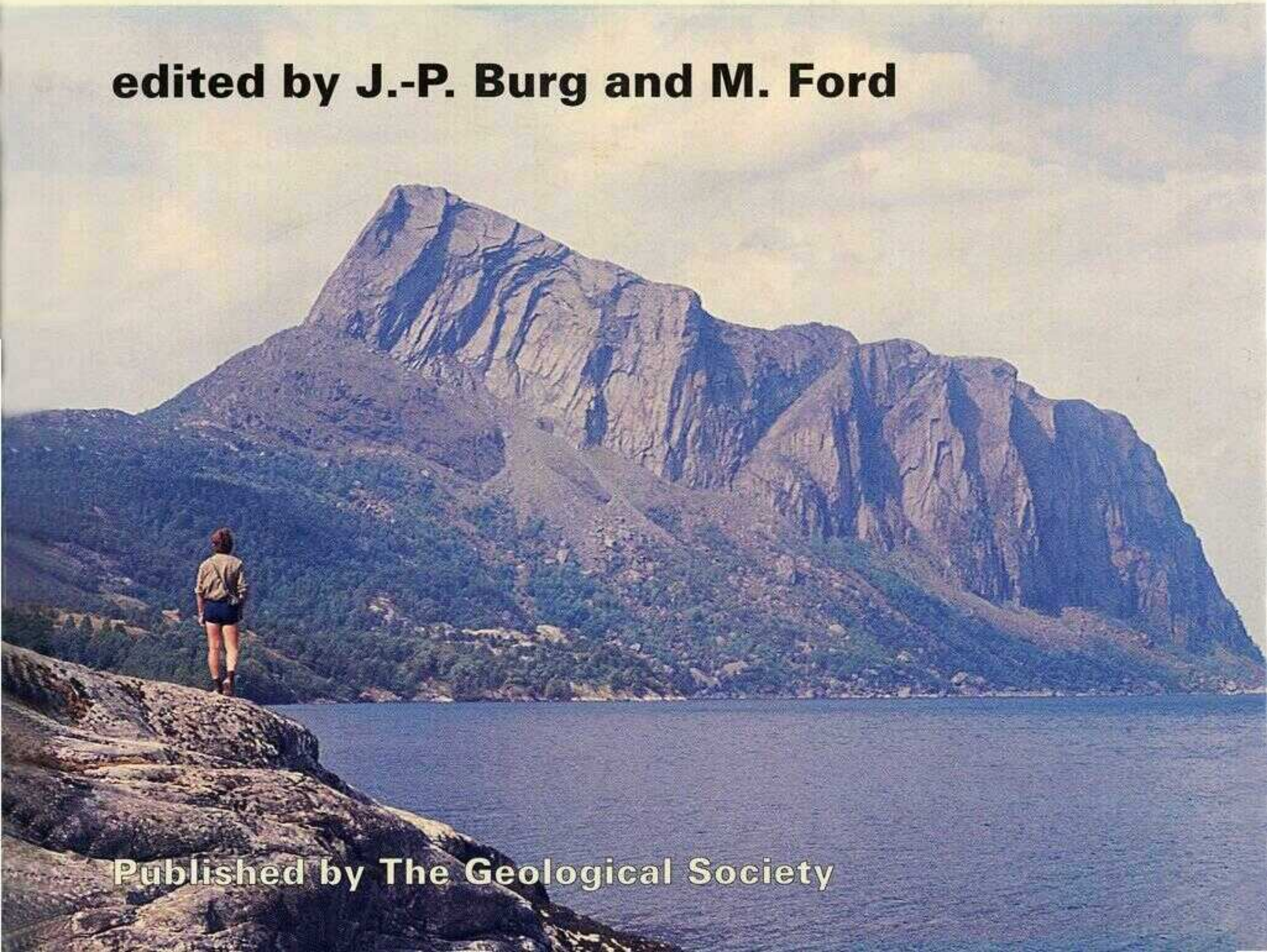
Orogeny Through Time

Geological Society
Special Publication
No. 121

edited by J.-P. Burg and M. Ford



Published by The Geological Society

GEOLOGICAL SOCIETY SPECIAL PUBLICATION NO. 121

Orogeny Through Time

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1997
Published by
The Geological Society
London

Structure and geodynamics of the Uralian orogen

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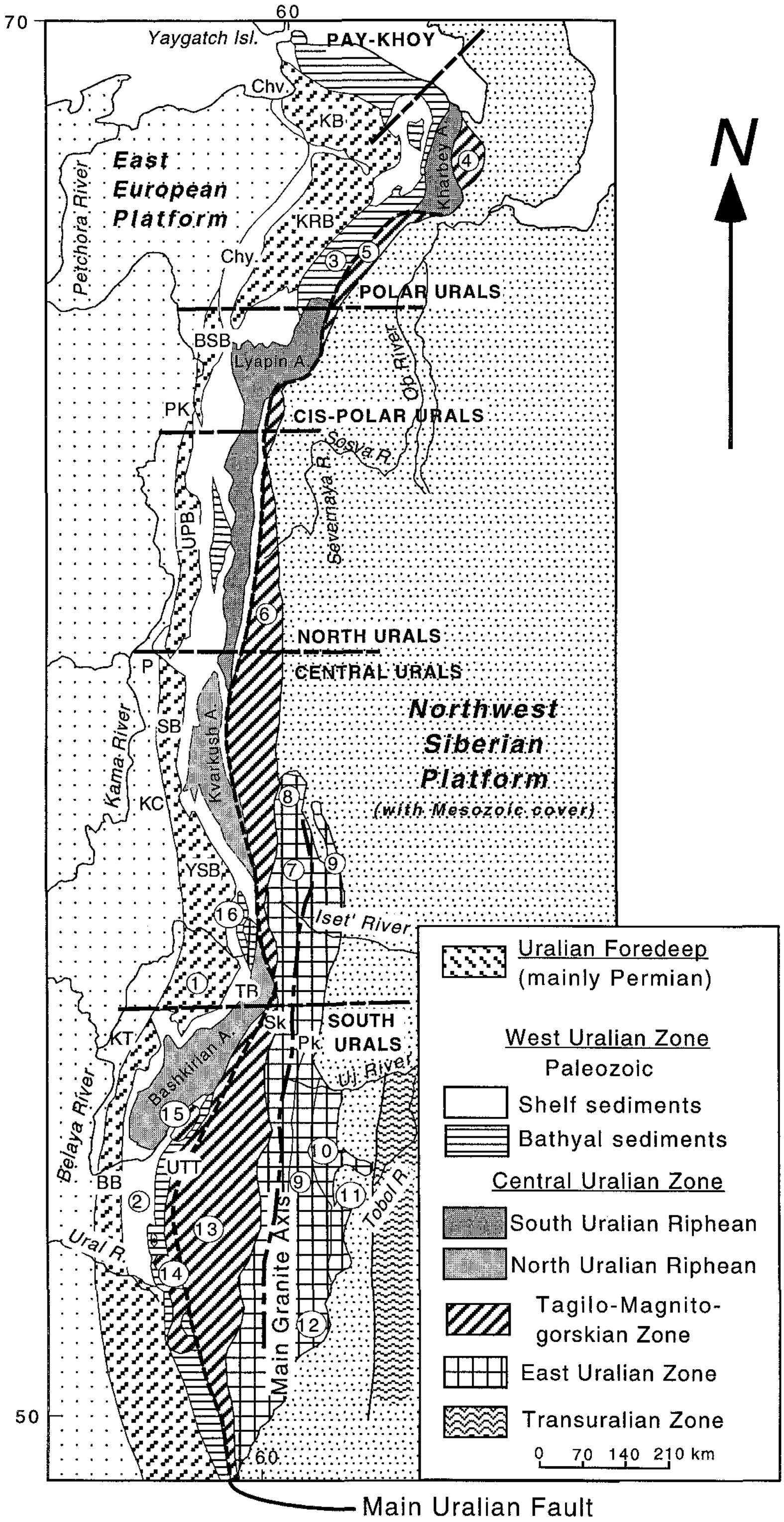
Abstract: The Urals are a Late Palaeozoic orogenic belt. The relicts of earlier orogens are traced in its basement. In particular, the Late Vendian pre-Uralian orogen is reconstructed and identified as a part of the Late Precambrian Cadomian orogen. The Uralian orogeny was preceded by Late Cambrian–Early Ordovician epicontinental rifting and formation of the Paleo-Uralian ocean whose remnants are Palaeozoic ophiolites. Calc-alkaline volcanites and plutons, typical of active margins, are widely developed in the eastern Urals. The Uralian foldbelt results from oblique collision between the East European (Laurussia) passive margin and the active margin on the Kazakhstanian continent. Collision began in the south of the Urals and moved, wave-like, to the north. The eastern and northern parts of the Urals have been affected by the Middle Jurassic Cimmerian intracontinental (intra-Pangaea) shortening. The Uralian–Cimmerian mountain belt was eroded and partially inundated by seas in the Late Jurassic—Early Cretaceous times and has been reactivated since the Oligocene in response to a recent intracontinental shortening.

The Urals are a Late Palaeozoic foldbelt that also experienced Mid-Jurassic Cimmerian deformation in its eastern and northern parts. The north–south-trending mountain range, approximately 2000 km long, is the geographic Europe–Asia boundary and is commonly divided into the Polar, Cis-Polar, Northern, Central and Southern Urals (Fig. 1). The characteristic feature of the fold belt is a distinct, though disturbed, linearity of tectonic zones. A continental passive margin to the west has been underthrust below units derived from a marine domain juxtaposed against a calc-alkaline palaeo-active margin. Thanks to Late Cenozoic tectonic movements the tectonic zones are all exposed in the Southern Urals. In the north, the easternmost zones are covered by the Mesozoic and Cenozoic sediments of the West Siberian basin.

The Uralian foldbelt is one of the oldest and richest mining regions of Russia. Therefore, it has attracted the attention of many geologists among whom one should mention Murchison (the founder of the Permian system), Karpinsky, (the proponent of the contractionist ideas who suggested that the changes in the Ural's strike were influenced by the outline of the rigid Russian plate) and Shatsky (who established the Riphean system in the Urals, discovered relicts of a Late Proterozoic foldbelt and developed the theory of relationships between geosynclines and platforms).

Understanding the general features of the Uralian structure and history has depended much on the development of general tectonic ideas. Publication of Wegener's 'Die Enstehung der Kontinente' (translated into Russian in 1924) and of the important works of Argand and Staub, led to a mobilist model of the Urals in the Thirties. In the 1940s and up to the 1960s, a fixist paradigm took over and 'charriage' (thrusting) practically became a prohibited word in publications concerning the Urals. Moreover, it is in the Urals that the concept of deep-seated faults was proposed by Peyve (1945). It was initially thought that these faults, such as the Main Uralian Fault, were near-vertical, reached deep into the mantle, controlled magmatism and metallogeny and were intrinsically a proof that continents could not drift over the mantle. For several decades these ideas were foremost in all tectonic interpretations and are still propounded by some researchers (note deep-seated faults in Fig. 2). At the same time, the Urals were regarded as an exemplary geosyncline. In 1972, in light of the introduction of plate tectonics, Peyve and Ivanov proposed that the Urals represent a closed Palaeozoic ocean. The first tectonic map at a scale of $1:10^6$ based on plate tectonic ideas was published in 1977 by Peyve *et al.* Subsequent work has accumulated a considerable volume of information supporting this interpretation (e.g. Kamaletdinov 1974; Perfilyev 1979; Puchkov 1979, 1991, 1993; Ruzhentsev 1986; Ivanov *et al.* 1986; Savelyeva 1987; Yazeva *et al.* 1989; Seravkin *et al.* 1992; Svyazhina *et al.* 1992).

From Burg, J.-P. &Ford, M. (eds), 1997, *Orogeny Through Time,* Geological Society Special Publication No. 121, pp.201–236.


70
60
Yaygatch Isl.
PAY-KHOY
Chv.
KB
East European Platform
Petchora River
KRB
Khabey A.
4
Chy.
3
5
POLAR URALS
BSB
Lyapin A.
Ob River
PK
CIS-POLAR URALS
Sosva R.
Severnaya R.
UPB
6
NORTH URALS
CENTRAL URALS
P
SB
Kama River
Kvarkush A.
Northwest Siberian Platform
(with Mesozoic cover)
KC
8
9
YSB
7
16
Iset' River
1
TR
Sk
SOUTH URALS
KT
Pk
Uj River
Bashkirian A.
Belaya River
15
10
UTT
BB
2
9
11
Tobol R.
13
Ural R.
14
Main Granite Axis
12
50
60
Main Uralian Fault
N
Uralian Foredeep (mainly Permian)
West Uralian Zone
Paleozoic
Shelf sediments
Bathyal sediments
Central Uralian Zone
South Uralian Riphean
North Uralian Riphean
Tagilo-Magnitogorskian Zone
East Uralian Zone
Transuralian Zone
0 70 140 210 km

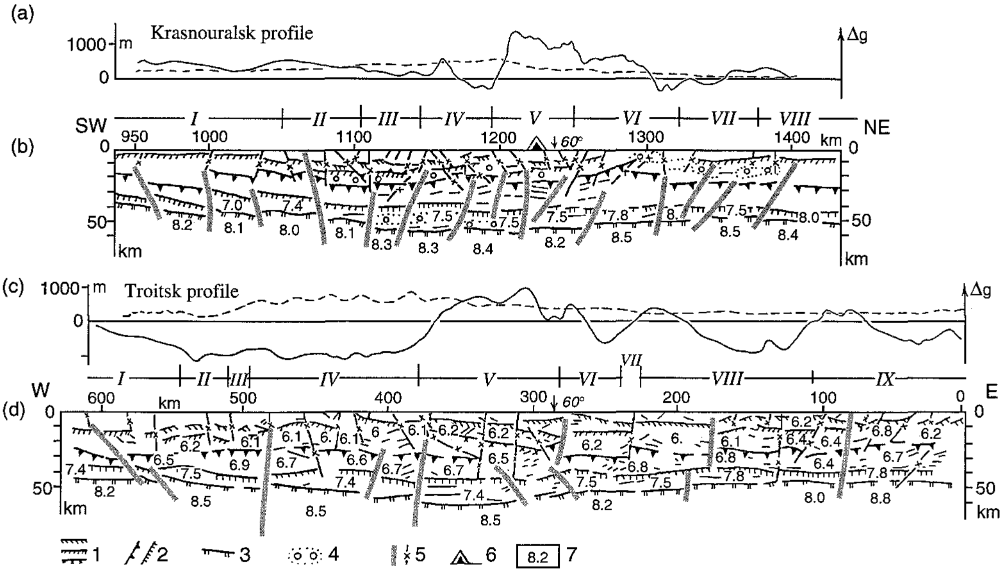


Fig. 2. Geophysical data from two profiles through the Urals (located on Fig. 3). In (a) and (c) a topographic profile (dashed line) and a gravity anomaly profile (solid line, no scale given) are shown for each profile, (b) and (d) show deep seismic sounding sections (very generalized after Avtoneev *et al.* 1991). Key: 1 and 2, unspecified boundaries of different, crustal seismic layers; 3, Moho surface; 4, anomalously low velocity zones; 5, hypothetical deep-seated faults of different order; 6, the Uralian Super-deep borehole; 7, layer velocities in km s^{-1}. Structural zones: I, East European platform; II, Uralian foredeep; III, West Uralian Zone; IV, Central Uralian Zone; V, Taglio-Magnitogorskian zone; VI and VII, Central Uralian zone; VIII, Transuralian zone; IX, Kazakhstanian 'Caledonides'.

Our understanding of the deep structure of the Urals has been improved considerably by a combined analysis of magnetic and gravity fields. More than 15 Deep Seismic Sounding (DSS) profiles and more than 20 seismic reflection profiles have been completed (e.g. Necheukhin *et al.* 1986; Avtoneev *et al.* 1991; Sokolov, 1992). This paper gives a summary of the current state of knowledge on the Urals.

Structural zonation of the Urals

The Urals are divided into six sub-longitudinal zones (Fig. 1), that differ both in their structure and stratigraphy. From west to east they are (1) the Uralian Foredeep, (2) the West Uralian, (3) the Central Uralian, (4) the Tagilo-Magnitogorskian, (5) the East Uralian and (6) the Transuralian zones.

Zones 1, 2 and 3 represent the former passive margin of the East European (Euramerian, Laurussia) continent (Puchkov 1979). This margin formed from the Late Cambrian to the Early Ordovician and was stable during Ordovician, Silurian and Devonian times. In the Late Palaeozoic, the platform was deformed to become a part of the Uralian foldbelt. The East European basement comprises granitic and metamorphic rocks of Precambrian age (Gafarov 1970). The crust is 34–42 km thick (Necheukhin *et al.* 1986; Avtoneev *et al.* 1991) (Figs 2 & 3). Zone 3 is bounded to the east by the Main

Fig. 1. Tectonic sketch map of the Urals showing the main tectonic zones and geographic sub-divisions of the orogen. Encircled numbers: 1, Ufimian amphitheatre. 2–13, Subzones: 2, Zilair; 3, Lemva; 4, Schchuchya; 5, Voykar; 6, Tagil; 7, Murzinka–Aduy; 8, Salda; 9, East Uralian volcanics; 10, Troitsk; 11, Denisovka; 12, East Mugodzhary; 13, Magnitogorsk; 14–16, tectonic klippen in the West Uralian zone, containing ophiolites or serpentinitic melange; 14, Sakmara; 15, Kraka; 6, Bardym (Nyazepetrovsk); A, Four anticlinoria of the Central Uralian zone; TR, Taratash complex. Transversal structural elements of the Uralian foredeep. Uplifts: KT, Kara-Tau; KC, Kosva–Chusovaya; P, Polyud; PK, Pechora–Kozhva; Chy, Chernyshov uplift; Chv, Chernov uplift. Basins: BB, Belsk; YSB, Yuryuzan–Sylva; SB,Solikamsk; UPB, Upper Pechora; BSB, Bolshaya Synya; KRB, Kosyu–Rogovaya; KB, Korotaikha; PK, Poletayevka area; UTT, Ural-Tau metamorphic terranes; SK, Selyankino.

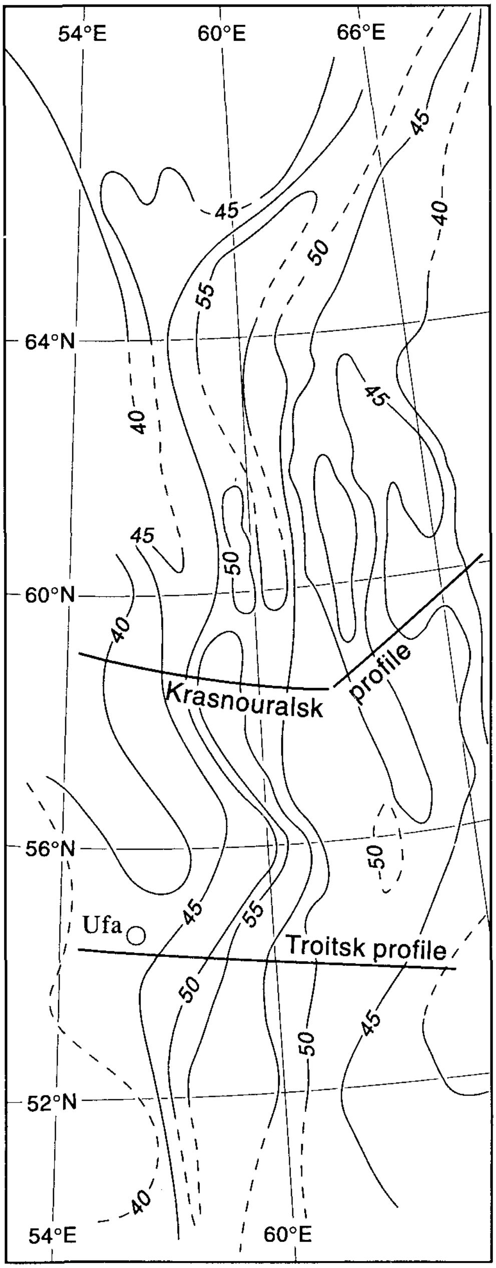


Fig. 3. Thickness of the crust in the Urals and adjacent areas (after Avtoneev *et al.* 1991; isopleths in km). Compiled from gravity anomalies and 16 DSS profiles.

Uralian Fault, the principal suture marked by a serpentinitic melange and inclined to the east by 20 to 40–50° (locally steeper). It may flatten at depth, as suggested by seismic data (Sokolov 1992; Petrov *et al.* 1994) (Figs 4 & 5).

The Uralian foredeep (Zone 1)

The Uralian foredeep, 50–75 km wide, is filled with Permian flysch and molasse of eastern provenance, up to 6 km thick (Nalivkin 1949; Makedonov 1965; Chuvashov & Dyupina 1973) underlain by 4–7 km thick Ordovician-Carboniferous shelf deposits (Fig. 6), which, in turn, unconformably cover Precambrian sedimentary, metamorphic and magmatic complexes. The western boundary of the foredeep is marked only in the Southern Urals by a chain of barrier reefs of Early Permian age (Asselian to Early Artinskian; Chuvashov & Nairn 1993). The terrigenous facies of the eastern provenance are spread far onto the platform, and the western boundary of the foredeep is usually expressed only by a more or less pronounced downward bend of the top surface of the carbonates underlying the molasse and in a corresponding eastward increase in the molasse thickness.

Facies changes of the foredeep sediments are complex, but the main steps in the foredeep development are the same at all latitudes. The foredeep began with the establishment of a deep-water basin on shelf sediments, west of the orogenic front. The basin was filled by molasse and flysch sediments grading westward into deep-water facies and still further west into reefs and biostromes (Fig. 7). Facies boundaries are diachronous (discussed later in this paper). The basin was filled with depositional evaporites of Kungurian (latest Early Permian) age. In the north the evaporites are replaced by terrigenous sediments with paralic coals. The Late Permian is represented in the foredeep by shallow marine, lacustrine and continental sediments, mostly terrigenous, red-coloured and variegated in the south, grey-coloured and coal-bearing in the north.

The eastern boundary of the foredeep was affected by westward thrusting. To the east the molasse and flysch are preserved in some deep synclines of the West Uralian fold zone. The outer (western) subzone of the foredeep is characterized mostly by smooth, open, non-linear folds typical for platform areas; the inner (eastern) subzone is characterised by thrusts and folds of a thin- to medium-skinned type (Puchkov 1975; Kazantsev 1984; Yudin 1994) (Fig. 4). Most of the structures of the inner foredeep are west-vergent. There are also some subordinate back-thrusts or underthrusts. In the Northern and Polar Urals seismic profiles suggest the presence of wedge-like (klinoform) structures composed mainly of Devonian, Carboniferous and Early Permian carbonates, thrust under the Permian molasse (Sobornov & Bushuev 1992; Sobornov & Tarasov 1992; Fig. 8).

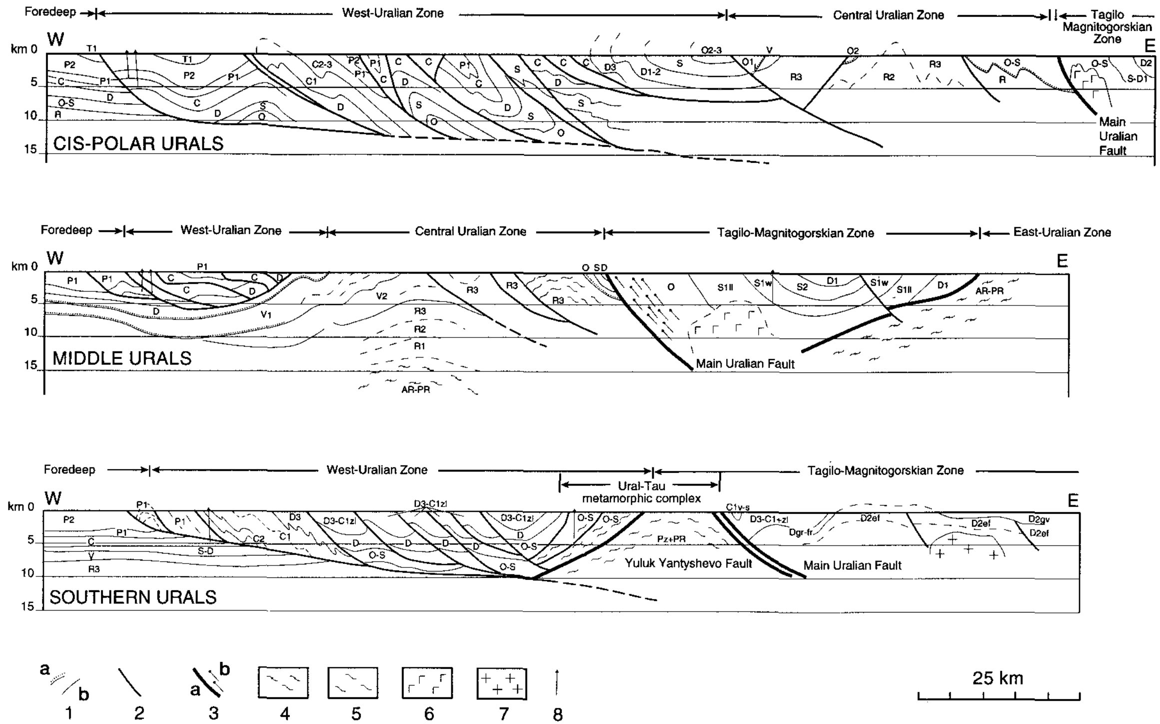


Fig. 4. Geological sections (located in Fig. 23) across the Urals, drawn after the Zilair–Kugarchi and Kushva–Serebryanka CDP seismic profiles, the SG4 near-vertical reflection profile, drilling data and geological observations (Puchkov 1975 and unpublished data; Yudin *et al.* 1983; Ablizin *et al.* 1982; Sokolov 1992; Kazantsev 1984; Seravkin *et al.* 1992). la, transgressive boundary; 1b, normal stratigraphic boundary, extrapolated where dashed; 2, faults, extrapolated where dashed; 3, major fault complex with a, serpentinitic melange or b, blastomylonites; 4, metamorphic complexes derived from Archaean–Proterozoic rocks; 5, metamorphic complexes derived from Riphean and/or Palaeozoic rocks; 6, gabbro of the Platinum-bearing Belt; 7, granites, 8, important wells. Stratigraphic lettering: AR–PR, Archaean–Early Proterozoic; R, Riphean; V, Vendian; O, Ordovician; S, Silurian (Sll, Llandoverian, Sw, Wenlockian); D, Devonian (Def, Eifelian; Dzv, Givetian; Dfr, Frasnian; D3-Clzl; Zilair series (Frasnian–Tournaisian greywacke)), C, Carboniferous; P, Permian. Subscripts 1, 2 and 3 indicate Upper, Middle and Lower respectively.

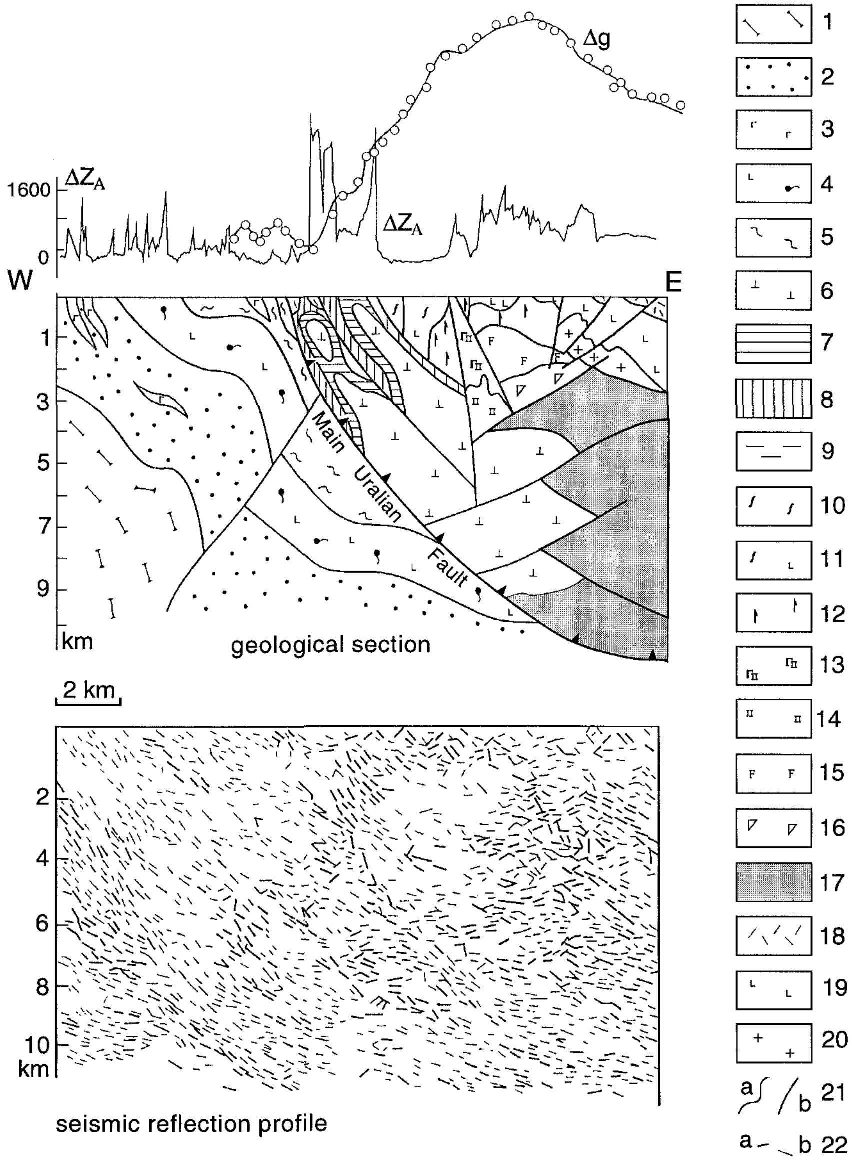


Fig. 5. Geophysical data and geological interpretation along a section across the Main Uralian Fault in the Northern Urals (located in Fig. 23, adapted from Petrov & Puchkov 1994). *1–5, Palaeocontinental sector:* 1, pre-Palaeozoic metamorphic complexes; 2, quartzites and shales; 3, gabbro–diabase; 4, metabasalts intercalated with silty shales; 5, metabasalts intercalated with silty shales. *6–10, Rocks of intensely deformed zone:* 6, dunites and harzburgites; 7, serpentinized peridotites; 8, serpentinites; 9, carbonaceous shales; 10, tuff shales. *11–20, Rocks of less intensely deformed zone:* 11, greenschist metabasalts; 12, sheeted dykes; 13, gabbro-norites; 14, pyroxenites, gabbro-amphibolites; 15, foliated amphibolites; 16, olivine gabbro; 17, mafic and ultramafic rocks undifferentiated; 18, Ordovician rhyolites; 19, Ordovician basalts; 20, plagiogranites. 21: a, Lithological boundaries; b, faults. 22: a, strong and b, weak seismic reflectors. ΔZ_A, intensity of the magnetic field; Δg, relative intensity of the gravity field (no scale given).

Most of the thrust-and-fold structures of the foredeep were formed during the Late Palaeozoic collisiol. In the southernmost and northern parts of the foredeep where Kungurian evaporites have a sufficient thickness, north–south trending salt ridges and oval domes are traced (Fig. 9).

Structures of the foredeep include not only

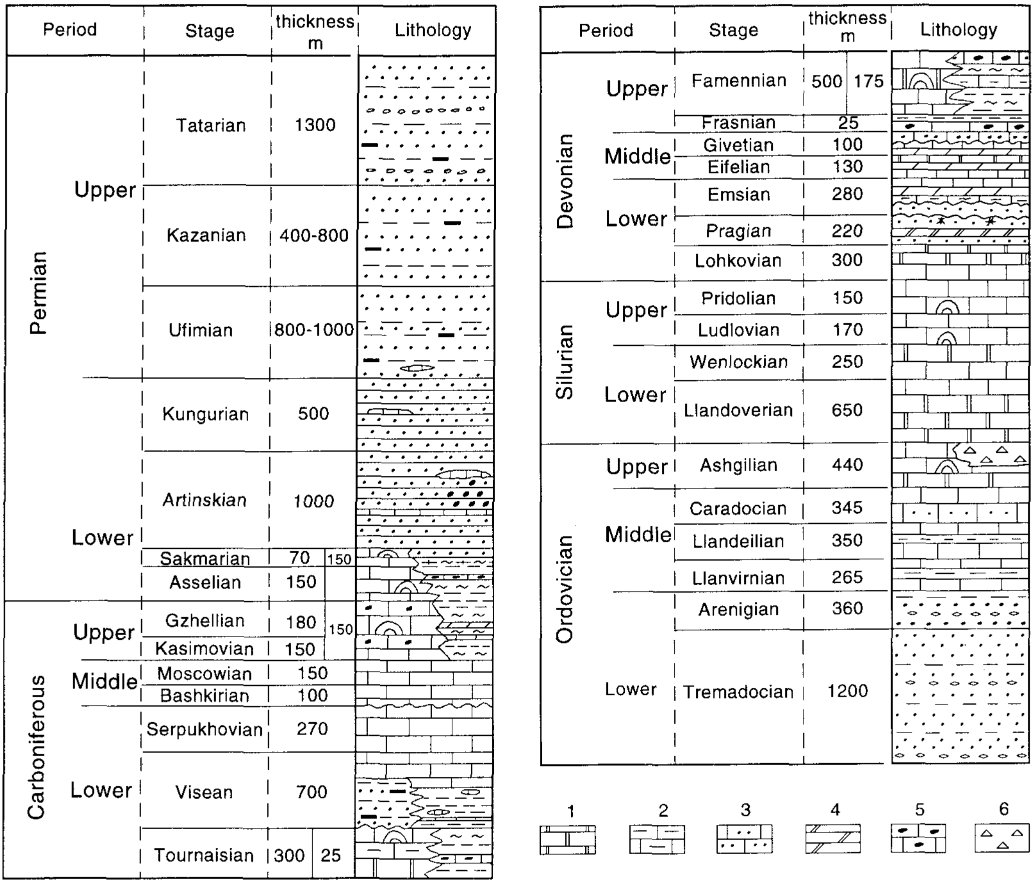


Fig. 6. Summarized section of the Palaeozoic deposits of the Uralian foredeep and West Uralian zone in the Cis-Polar Urals (Schchugor and Kozhim rivers) compiled after the Ail-Russian Stratigraphic Committee (1993) and author's personal data. 1, dolomitized limestones; 2, shaly limestones; 3, sandy limestones; 4, dolomitic marls; 5, cherty limestones; 6, carbonate breccia. Other symbols as in Fig. 10.

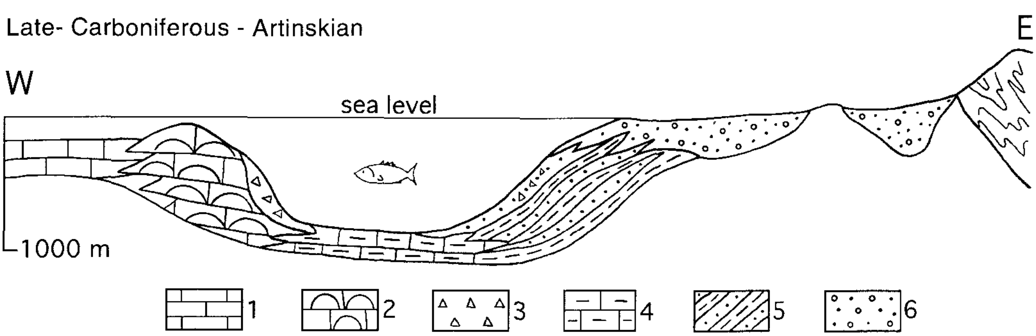


Fig. 7. Cartoon summarizing the principal lithofacies across the Late Carboniferous–Artinskian Uralian foredeep (after Nalivkin 1949 and Chuvashov *et al.* 1984). 1, shallow-water sediments, mostly bedded carbonates; 2, reefal limestones; 3, carbonate olistostrome; 4, basinal shales, cherts, marls; 5, turbidites; 6, molasse.

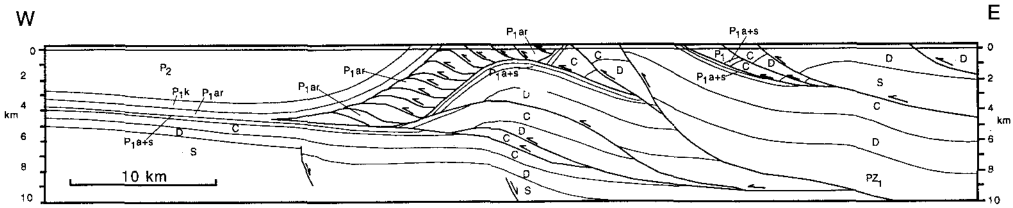


Fig. 8. Geological section across the boundary between the Uralian foredeep and West Uralian zone in the southern part of the Cis-Polar Urals, based on a CDP seismic profile (Sobornov & Bushuyev 1992). Location on Fig. 23, Stratigraphic lettering as on Fig. 4. Permian subunits: P_{1k}, Kungurian ; P_{1ar}, Artinskian; P_{1a+s}, Asselian and Sakmarian.

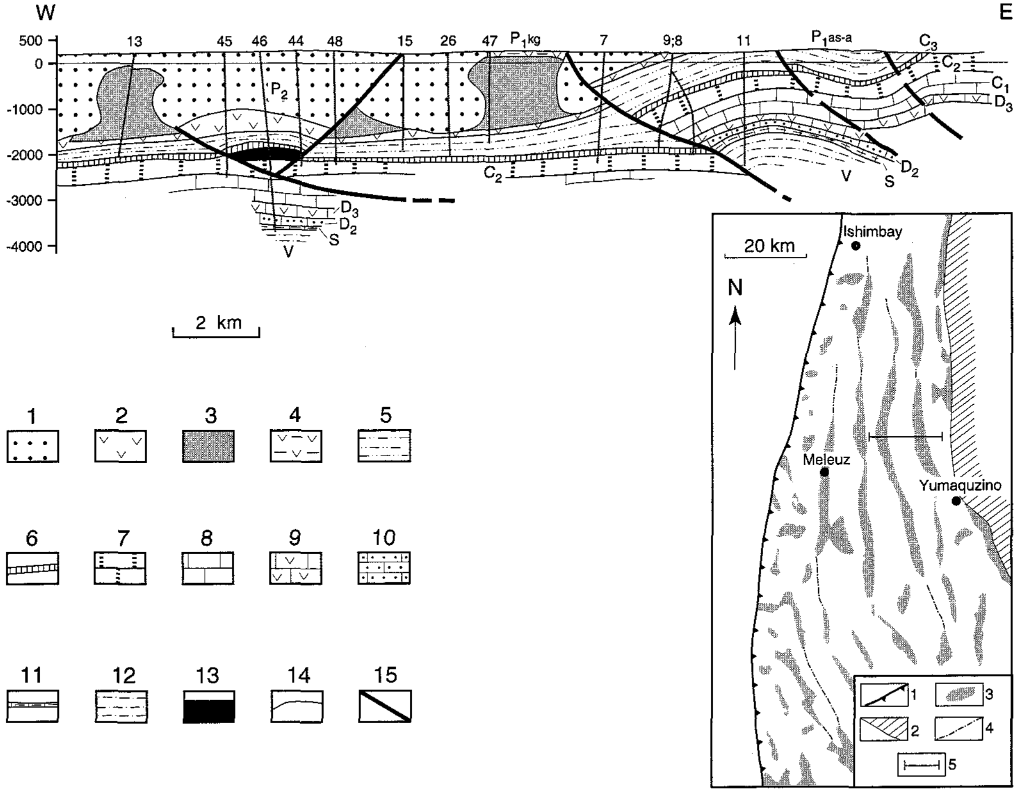


Fig. 9. Geological section across salt ridges (indicated on inset) (from Kamaletdinov *et al.* 1977, modified according to later seismic data). 1, Late Permian terrigenous sediments; 2–4, Kungurian stage (P_{kg}); 2, clays, anhydrites; 3, salt; 4, terrigenous sediments with gypsum; 5, Asselian, Sakmarian and Artinskian (P_{as-a}) terrigenous sediments; 6, Late Carboniferous limestones, marls and siltstones (C_3); 7, Middle Carboniferous limestones and dolomites (C_2); 8, Early Carboniferous limestones and dolomites with shale intercalations (C_1); 9, Late Devonian limestones (D_3); 10, Mid-Devonian limestones, sandstones and shales (D_2); 11, Silurian marls, dolomites and sandstones (S); 12, Vendian terrigenous sediments (V); 13, oil pool; 14, Stratigraphic boundaries, 15, thrusts. Numbers near subvertical lines mean wells.
Inset map (located on Fig. 23) showing the salt ridges in the southernmost part of the Pre-Uralian foredeep. 1, western boundary of the foredeep; 2, area where Kungurian deposits are absent; 3, salt ridges; 4, chains of salt ridges; 5, line of section.

longitudinal, but also transverse (NW–SE) elements, partially inheriting their strikes from the structures of the crystalline basement. Among them (from south to north, Fig. 1):

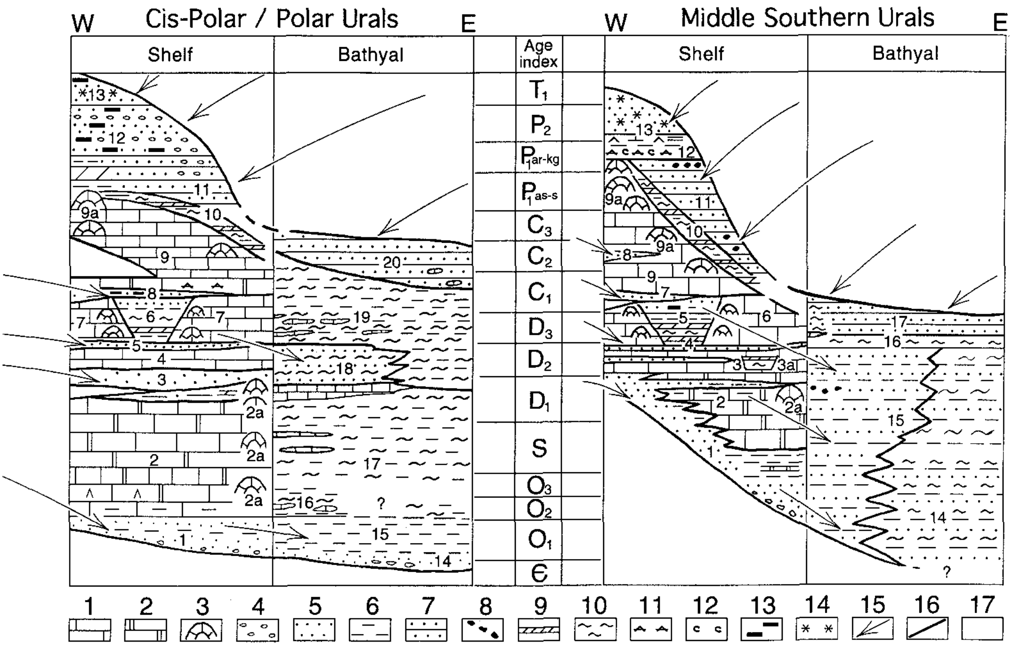


Fig. 10. Schematic correlation of Palaeozoic sedimentary formations belonging to the passive margin of the East-European continent. Symbols in boxes: 1, limestones; 2, dolomites; 3, big biostromes and reefs; 4, conglomerates; 5, sandstones and siltstones; 6, siltstones and shales; 7, flysch; 8, olistostromes; 9, marls; 10, cherts; 11, sulphates; 12, salt; 13, coal; 14, red beds; 15, direction of terrigenous influx; 16, boundaries of the most important formations; 17, sediments eroded or not deposited.
Numbers in the figure refer to the most important formations. *Cis-Polar/Polar Urals.* 1, Telpos terrigenous oligomictic formation, up to 1600 m thick. 2, Kozhimian shallow-water carbonate formation, up to 2300 m thick; 2a, barrier reefs, individual build-ups up to 500 m high. 3, Philippchuk–Takata terrigenous oligomictic formation, up to 400 m thick. 4, Carbonate formation, up to 200 m. 5, Pashiya terrigenous oligomictic formation, up to 26 m. 6, Formations of the Kama–Kinel trough system: Domanik basinal starved formation, up to 300 m thick, overlain by a Famennian–Tournaisian carbonate-terrigenous formation, up to 1000 m thick. 7. Carbonate formation with biostromes and reefs, up to 1300 m thick, aligning the Kama–Kinel trough system. 8. Uglenosnaya (coal-bearing) terrigenous oligomictic formation, up to 200 m thick. 9, Carbonate formation, up to 600 m thick; 9a, barrier reefs and thick biostromes, up to 200 m thick. 10, Basinal starved formation, up to 50 m thick. 11, Flysch of the Uralian foredeep, up to 1000 m thick. 12, Coal-bearing molasse, up to 3300 m thick. 13, Red-coloured and variegated grading upwards to a coal-bearing molasse, 2200 m thick. 14, Pogurey terrigenous oligomictic formation, up to 600 m thick. 15, Grube-Yu fine-grained terrigenous formation, up to 1000 m thick. 16, Kachamylk carbonate–terrigenous formation, up to 1300 m thick. 17, Kharota carbonaceous limestone–cherty–shaly formation, up to 300 m thick. 18, Paga cherty–terrigenous oligomictic formation, up to 600 m thick. 19, Kolokolnya limestone–cherty–shaly formation, up to 500 m thick. 20, Kechpel and Yayu flysch formations, up to 2000 m thick.
Middle Southern Urals. 1, Diachronous terrigenous oligomictic formation, up to 400 m thick. 2, Shallow-water carbonate formation, up to 570 m thick; 2a, Barrier reef, up to 1200 m thick. 3, Carbonate–terrigenous formation, up to 200 m thick; 3a, Infradomanik basinal formation, up to 80 m thick. 4, Pashiya terrigenous oligomictic formation, up to 10 m thick. 5, Kama–Kinel trough system: Domanik basinal formation, up to 350 m thick, overlain by Late Tournaisian–Early Viséan terrigenous formation, up to 500 m thick. 6, carbonate formation, with barrier reefs aligning the Kama–Kinel trough system, up to 700 m thick. 7, Uglenosnaya (coal-bearing) terrigenous oligomictic formation, up to 60 m thick. 8, Carbonate–terrigenous oligomictic formation, up to 75 m thick. 9, Carbonate formation, up to 2500 m thick; 9a, barrier reefs at the western margin of the Uralian foredeep, up to 1000 m thick. 10, Basinal formation, up to 100 m thick. 11, Flysch and olistostrome formation, up to 2500 m thick. 12, Evaporite formation, up to 500 m thick. 13, Variegated molasse, up to 3000 m thick. 14, Uzyan cherty-terrigenous oligomictic formation, up to 1000 m thick. 15, Suvanyak terrigenous oligomictic group, up to 4000 m thick. 16, Ibragimovo cherty formation, up to 150 m thick. 17, Zilair flysch formation, up to 2000 m thick.

Kara-Tau, Kosva–Chusovaya, Poliud Range, Pechora–Kozhva, Chernyshov Range and Chernov Range uplifts. These structures differ in their morphology, origin and age. The Kara-Tau and the Poliud Range are combinations of a sinistral strike-slip fault and several folds and thrusts; the Kosva–Chusovaya is a gentle saddle-like uplift under the molasse. Pechora–Kozhva is a Devonian aulacogen inverted in the Late Palaeozoic. Chernyshov and Chernov are Mid-Jurassic, narrow, linear fold-and-thrust zones probably connected to detachments in the Early Palaeozoic strata deep under the basin. These transverse uplifts divide the foredeep into several semi-isolated basins: Belsk, Yuryuzan–Sylva, Solikamsk, Upper Pechora, Bolshaya Synya, Kosyu–Rogovaya and Korotaikha (Fig. 1).

The West Uralian zone (Zone 2)

The West Uralian zone comprises predominantly intensely folded and thrust Lower and Middle Palaeozoic sediments characterizing the former passive margin of the East European continent. There is no conspicuous facies change at the boundary between the Uralian foredeep and the West Uralian zone. Such a change, partially affected by later thrusts, occurs further to the east within the zone, as an abrupt transition from shelf to bathyal sediments (Figs 6 & 10). Sedimentary facies changes occur across the passive margin as well as along its 2000 km length.

Shelfsediments. Figure 10 shows synoptic stratigraphic sections of the shelf sediments in the western slopes of the Urals. The real sections are most complete in the northern parts of the West Uralian zone, where the thickness of the pre-flysch Palaeozoic sediments is up to 6–7 km. In the Middle and Southern Urals these sediments are much thinner (up to 2.5–3 km), and here, in the western sections of the zone, the Ordovician, Silurian and Lower Devonian sediments are absent, so the Middle Devonian strata unconformably overlie Riphean and Vendian sediments.

The complete sections of shelf sediments, most typical for the northern and easternmost parts of the zone (Figs 6 & 10) are composed of transgressive Ordovician quartzites and basal conglomerates grading upsection to shallow water dolomites and limestones of Silurian–Earliest Devonian age. Among the Upper Ordovician and Silurian limestones, a reefal facies formed barriers along the eastern margin of the shelf, mostly in the northern and central areas of the Urals. The Lower Devonian regressive succession of argillaceous limestones, dolomitic marls, siltstones and shales, are followed by Emsian transgressive quartzites, sandstones and siltstones grading upwards mostly into shallow-water open-sea limestones. The longest Lower Devonian barrier reef is traced along the margin of the shelf zone from the Polar to the Southern Urals. In the south Middle Devonian basinal shales, marls and cherts (so-called infradomanik) developed. In the Latest Mid-Devonian a new transgressive series was deposited with thin quartzites and shales in the bottom. Over the area of development of the Upper Givetian terrigenous facies and open-sea limestones, the so-called Kama–Kinel system of deep-water troughs was established. The troughs can be traced from the platform directly into the West Uralian zone as the best evidence of their former unity (Figs 10 & 11). The basinal, 'domanik' facies in the axial parts of the troughs is represented by a starved, condensed unit of marls, cherts and oil shales. The troughs are bordered by reef limestones. This type of sediment distribution persisted through the Famennian and Tournaisian, related to the high stand of sea level across the platform. The regressive Lower Viséan and transgressive Middle Viséan sediments are characterized by the wide development of terrigenous and carbonate-terrigenous facies, including quartzites, shales and siltstones with coal layers. The Kama–Kinel troughs were filled with Early Viséan sediments and ceased to exist. The Early Carboniferous, Late Viséan–Serpukhovian as well as the Mid-Carboniferous Bashkirian stage are represented mostly by pure shallow-water limestones. The next very important transgressive–regressive boundary of the strati graphic sequences, marked by unconformity and the deposition of terrigenous sediments is within the Moscovian (Middle Carboniferous), but in the West Uralian zone this unconformity is not pronounced due to a general eastward inclination of the shelf. Therefore, the Middle–Upper Carboniferous is represented in the West Uralian zone predominantly by shallow-water limestones, restricted above, in many places, by a stratigraphic unconformity. The Middle Carboniferous of the southern part of the shelf area within the West Uralian zone displays the first signs of the westward terrigenous influx. From this time on, the area of sedimentation influenced by the eastern source of terrigenous material was widening to the west and north and the foredeep started to form above the shelf subzone (see the corresponding section of this paper). Two more major transgressive–regress-

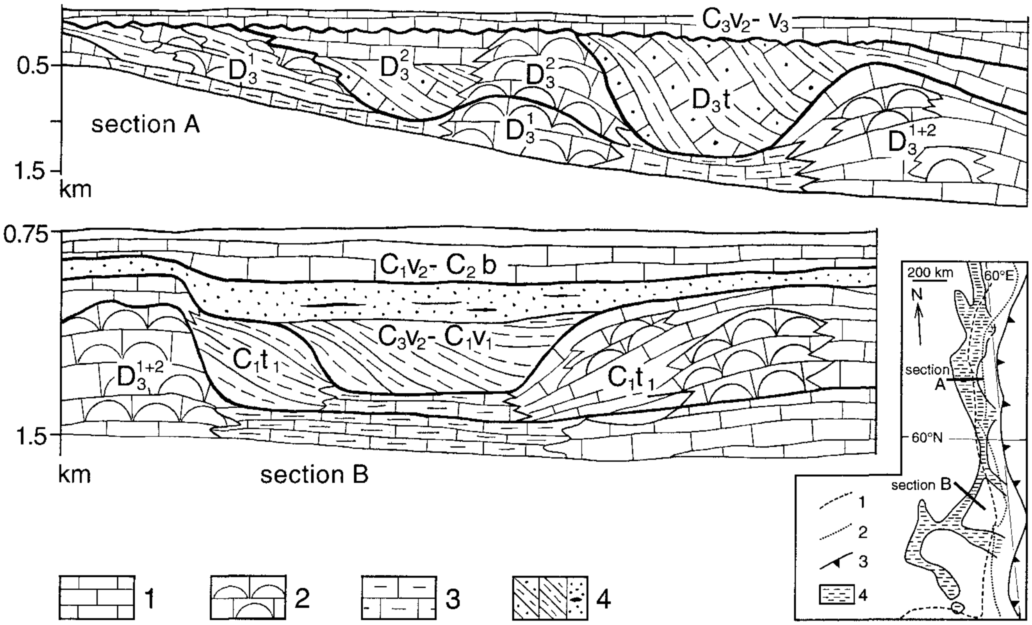


Fig. 11. Principal geological sections across the Kama–Kinel trough system (simplified after Parasyna *et al.* 1989). 1, Shallow-water shelf sediments (predominantly bedded carbonates); 2, reefal massifs and bioherms; 3, basinal (Domanik type) shales and marls marking the axis of the Kama–Kinel system of troughs; 4, terrigenous and carbonate-terrigenous sediments filling the troughs; left, siltstones, shales, oil shales, marls; centre, shales, siltstones; right, sandstones with coal seams. Sections located on inset map, where 1, Uralian foredeep boundary; 2, boundary of the West Uralian zone; 3, boundary of the Tagilo–Magnitogorskian zone; 4, Kama–Kinel troughs.

ive cycles of Early and Late Permian age developed as a background to the formation of the foredeep.

Bathyal sediments. The width of the bathyal zone varies from 10 to 60 km and is widest in the Southern and Polar Urals where the Zilair and Lemva synforms respectively (2 and 3, Fig. 1) occur. The bathyal complexes are best developed there, where the Precambrian rocks of the Central Uralian zone are almost absent. In contrast to the shelf facies, the areas of bathyal sediments are discontinuous, though wide enough for their main features to be studied (Fig. 1). Conodont studies have allowed considerable progress on their stratigraphy, leading to correlation of sections and determination of facies patterns (Puchkov 1979).

The Palaeozoic section of the bathyal complexes (Fig. 10), best studied in the Polar Urals, starts with Uppermost Cambrian sandstones. The Lower Ordovician is also terrigenous, green and red coloured, up to 2–2.5 km thick, siltstones being predominant. The Middle Ordovician in the westernmost bathyal sections, transitional to the shelf facies, comprises shales, limestones and cherts. The Middle Ordovician of the bathyal facies proper is represented by thin cherts in the Southernmost and Polar Urals. Upper Ordovician strata are not known. The Silurian and Early Devonian (Lohkovian) are represented by a very typical condensed unit of carbonaceous cherty shales and limestones, up to 250 m thick, covered by a marker horizon of tentaculite knotty limestones, several metres thick. Only in some areas of the Southern Urals are these cherts and limestones probably replaced by a more than 1000 m thick terrigenous series. The Middle Devonian is usually represented by up to 500 m of quartzitea, siltstones, shales and cherts. When the quartzites are absent the section is very condensed. The Upper Devonian is represented by cherts, locally intercalated with 100–300 m thick limestones. In the Southern Urals the cherts are overlain by up to 3000 m of greywacke flysch of Latest Frasnian–Tournaisian age of eastern provenance, polymictic, with fragments of cherts, volcanites and granites, with grains of chromspinel. In the Northern territories the cherty section are also in the Carboniferous, and the first greywackes do not appear earlier than the Late Viséan. The deep-water flysch trough existed here at least until the end of the Late Carboniferous (some additional details will be given later in the paper).

Thrusting is very characteristic for many areas in the West Uralian zone, with detachments in the sedimentary cover and along the cover/basement boundary. The detachment levels may be different depending on the lithologies in the different parts of the zone. In the southernmost and middle Urals the detachments under the Uralian foredeep and the West Uralian zone are situated mostly at the base and top of the Vendian, at depths of 1.5–4 km, and probably down to 10 km in the eastern parts of the zone. In the northern parts of the Urals, where the thickness of the Palaeozoic is greater, the main detachment may be situated at depths of 10 km and more, close to the cover–basement boundary and in Ordovician shales (medium- to thick-skinned tectonic style). Clays and evaporites of some horizons of the Devonian, Carboniferous and probably Permian acted as weaker horizons hosting detachments (Figs 4 & 6; Puchkov 1975; Kazantsev 1984; Yudin 1983, 1994; Dembovsky *et al.* 1990; Sobornov & Bushuev 1992).

As in the foredeep, the general vergence is to the West and there are wedge-like structures which may be regarded as underthrusts or backthrusts. Usually backthrusts are subordinate, with the exception of the westward-dipping Yuluk-Yantyshevo fault (Fig. 4c), the western boundary of the Ural-Tau complex in the Southern Urals.

Ophiolites and island-arc sediments (the Sakmara, Kraka and Nyazepetrovsk–Bardym allochthons of the West Uralian zone: 14, 15 and 16 in Fig. 1) have been thrust westward onto this zone. The oceanic thrust sheets are usually associated with serpentinite melanges and bathyal complexes of the passive continental margin. The bathyal complexes also form some independent allochthons, with a minimum displacement of 20 km (Puchkov 1979). The allochthons have been folded after their emplacement into 5–10 km wide synforms and antiforms. The best explored is the bottom of the Nyazepetrovsk–Bardym nappe which is penetrated by 5 boreholes to depths of between 500 and 1000 m (Puchkov & Ivanov 1982).

The Central Uralian zone (Zone 3)

The Central Uralian zone (Zone 3), up to 70–75 km wide, is characterized by well exposed Precambrian sedimentary, metamorphic and magmatic rocks which are, in some places, thrust over the rocks of the West Uralian zone (Fig. 4a).

The rocks of the Central Uralian zone are mostly Late Proterozoic in age (i.e. Riphean and Vendian, 1650–570 Ma, Keller & Chumakov 1983; Krasnobayev 1985). The recognition of Early Proterozoic rocks is problematic (they are probably developed in the cores of some thermal domes). Archaean rocks are found only in one place: the Taratash complex which is thought to be a fragment of the basement of the East European platform (TR, Fig. 1, Lennykh & Krasnobayev 1978), represented by polymetamorphic rocks which probably belonged to a greenstone belt (Lennykh 1986). The rocks experienced a granulitic metamorphism by the end of the Archaean, when enderbites, two-pyroxene crystalline schists, gabbro–diorite-gneisses and magnetite quartzites were formed. Later they were subjected to retrograde metamorphism varying from amphibolite to greenschist facies (Lennykh *et al.* 1978). Late Proterozoic complexes are represented in most of the sections by up to 13km of shallow-water terrigenous sediments with quartz and subarkose sandstones, siltstones, shales and carbonate biostrome horizons. Volcanites are a typical, though far from ubiquitous component of the sections, represented predominantly by sub-alkaline basalts and basalt–rhyolite complexes of ensialic geochemical character.

The Riphean sections of the southern and northern parts of the Urals differ first and foremost in the age and amount of volcanics in the series. In the Southern Urals the volcanites (sub-alkaline basalts and basalt–rhyolite complexes) are not very widely developed, being present at the base of the Early Riphean, in the lower part of the Middle Riphean and also in the Early Vendian (Parnachev 1981; Parnachev *et al.* 1981). In the northern parts of the Urals the maximum volcanic activity took place in the Late Riphean, leading to the formation of a widely developed basalt–rhyolite series and associated granite and gabbro intrusions (Goldin *et al.* 1973). Calc-alkaline volcanites are reported from the Late Riphean of the Polar Urals (Rumyantseva 1984). The Vendian is represented both in the southern and northern sections by a molasse-like series of polymictic conglomerates, sandstones and siltstones (Bekker 1968; Puchkov 1975).

The Late Proterozoic series are affected by a Barrovian-type metamorphism, localized in dome-like structures and dated as Late Vendian

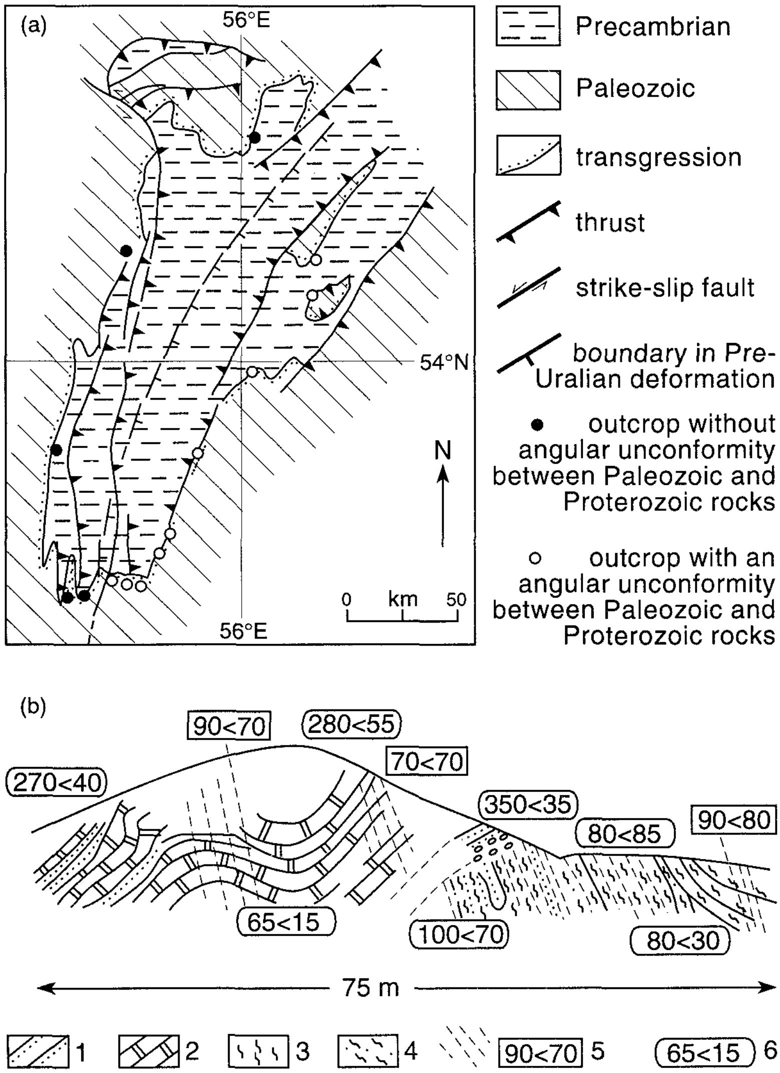


Fig. 12. Relationships between the Precambrian and Paleozoic complexes on the limbs of the Bashkirian anticlinorium (Fig. 1). (**a**) Relationships in mapview. (**b**) An example of an outcrop with an angular unconformity between the Vendian and Ordovician. 1 & 2, Ordovician: 1, quartz sandstones; 2, dolomites. 3 & 4, Early Vendian: 3, phyllite; 4, schistose siltstones and quartzites. 5 & 6, Strike and dip of: 5, cleavage; 6, layering. Location of (**a**) is shown in Fig. 23.

(Puchkov 1995). With increasing distance from these complexes to the west, the metamorphic grade of the sediments decreases to anchizone (deep catagenesis in Russian terminology; Anfimov 1986). Therefore, in the Central Uralian zone, relicts of the earlier, Vendian orogen are present. The restored general features of this orogen which differs strongly in structure and strike from the Uralian one, will be discussed later.

The Palaeozoic sediments of the Urals usually cover the Late Proterozoic with angular unconformity. So the structures in the Late Proterozoic are here the result of two orogenic deformations. But in some places, such as the western parts of the Bashkirian and Kvarkush anticlinoria (Fig. 1), the unconformity disappears, as well as the metamorphism, and the linear thrust-and-fold structures affecting the Late Proterozoic sediments are purely Palaeozoic in age (Uralian; Figs 12 & 13). The latter do not necessarily belong to the thin-skinned

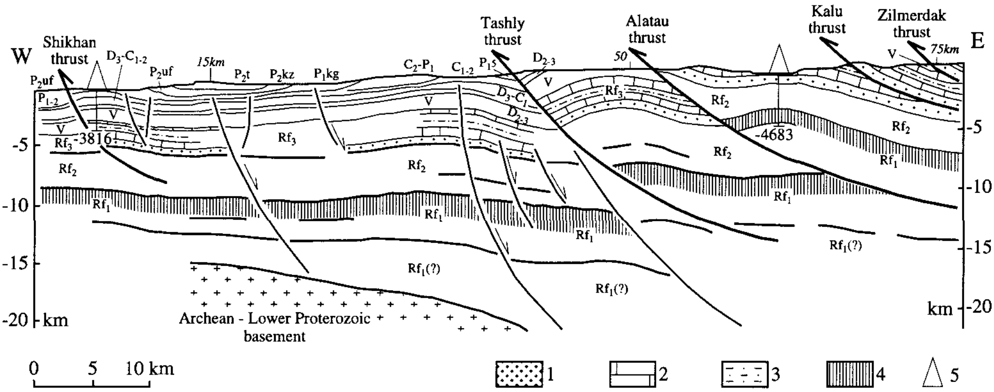


Fig. 13. Geological section across the western slope of the Southern Urals based on a CDP seismic profile (Skripiy & Yunusov 1989). Located on Fig. 23. 1, sandstones of the Upper Riphean Zilmerdak suite; 2, limestones and dolomites of the Upper Riphean Katav and Minyar suites; 3, terrigenous rocks of the Upper Riphean Inzer suite; 4, marker carbonate series of the Lower Riphean Bakal suite; 5, deep wells. $Rf_{1–3}$: terrigenous–carbonate complexes of the Lower-Upper Riphean, generating strong reflections; V, terrigenous Vendian complex; $D_{2–3}$, terrigenous-carbonate deposits of the Mid-Late Devonian age ('D' reflector); D_3–C_1 and $C_{1–2}$, carbonate complexes of the Late Devonian–Early Carboniferous and Early-Mid-Carboniferous, respectively, separated by 'U' reflector; C_2–P_1, Mid-Carboniferous–Early Permian carbonate complex, overlying the 'V' reflector. P_1s, P_1kg, P_2uf, P_2kz P_2tat: stages of the Permian (respectively, Sakmarian, Kungurian, Ufimian, Kazanian and Tatarian).

deformation predominant in the Palaeozoic cover. In these areas the detachment surfaces could be situated at depths of 10–15 km, probably because of the immense thickness of the Late Proterozoic sediments (Figs 4b & 13).

Structurally, the Central Uralian zone is often described as a chain of anticlinoria (from north to south: Kharbey, Lyapin, Kvarkush and Bashkirian, Fig. 1). Another anticlinorium, the Ural-Tau, is often listed among them (UTT, Fig. 1). But the structures exposed in the Ural-Tau Range present a special problem. Metamorphic terranes of this range, belonging to two complexes, Suvanyak and Maksyutovo, are traditionally attributed to Late Proterozoic. But new data, especially new finds of fauna, make this interpretation very doubtful. The Suvanyak complex, 250 km long and 10–20 km wide, is represented by thick quartzites, siltstones and shales metamorphosed in greenschist facies. It conformably underlies Frasnian cherts of the Ibragimovo suite and contains rare graptolites, brachiopods, conodonts, acritarchs and some other fauna in the range of Ordovician–Mid-Devonian. Zakharov & Puchkov (1994) interpret the Suvanyak complex as a series of Palaeozoic bathyal sediments of the passive continental margin. The Maksyutovo complex, 200 km long and 15 km wide to the east of the Suvanyak complex, is a famous site of the development of HP–LT (eclogite–glaucophane schist) metamorphism (Dobretsov 1974; Valizer & Lennykh 1988; Puchkov 1995). For a long time, the complex was thought to be composed of Riphean sedimentary and magmatic rocks of very contrasting primary ophiolitic and arkose types. The metamorphism was also thought to have occurred in the Riphean. Several recent finds of conodonts in marbles among the ophiolite-type succession (up to Late Silurian–Early Devonian in age according to Zakharov & Mavrinskaya 1994) as well as K–Ar ages for phengite (about 400 Ma, Valizer & Lennykh 1988) and Ar–Ar ages for eclogites (about 370 Ma, Matte *et al.* 1993), make a revised interpretation of this complex possible (Zakharov & Puchkov 1994). These authors proposed that the Maksyutovo metamorphic complex represents subducted and then exhumed accretionary fragments of a Devonian island arc and contains both Palaeozoc and probably Precambrian rocks of different types. During the Late Palaeozoic collision, the Maksyutovo block was folded into an antiform and thrust under the metasedimentary Suvanyak complex of a passive continental margin along the west-dipping Yantyshevo–Yuluk Fault, marked by a serpentinitic melange (Zakharov & Puchkov 1994; Fig. 4c). In some other places, complexes resembling the Maksyutovo are developed in the footwall of the Main Uralian Fault, mostly in the north of the Urals (Nerka–

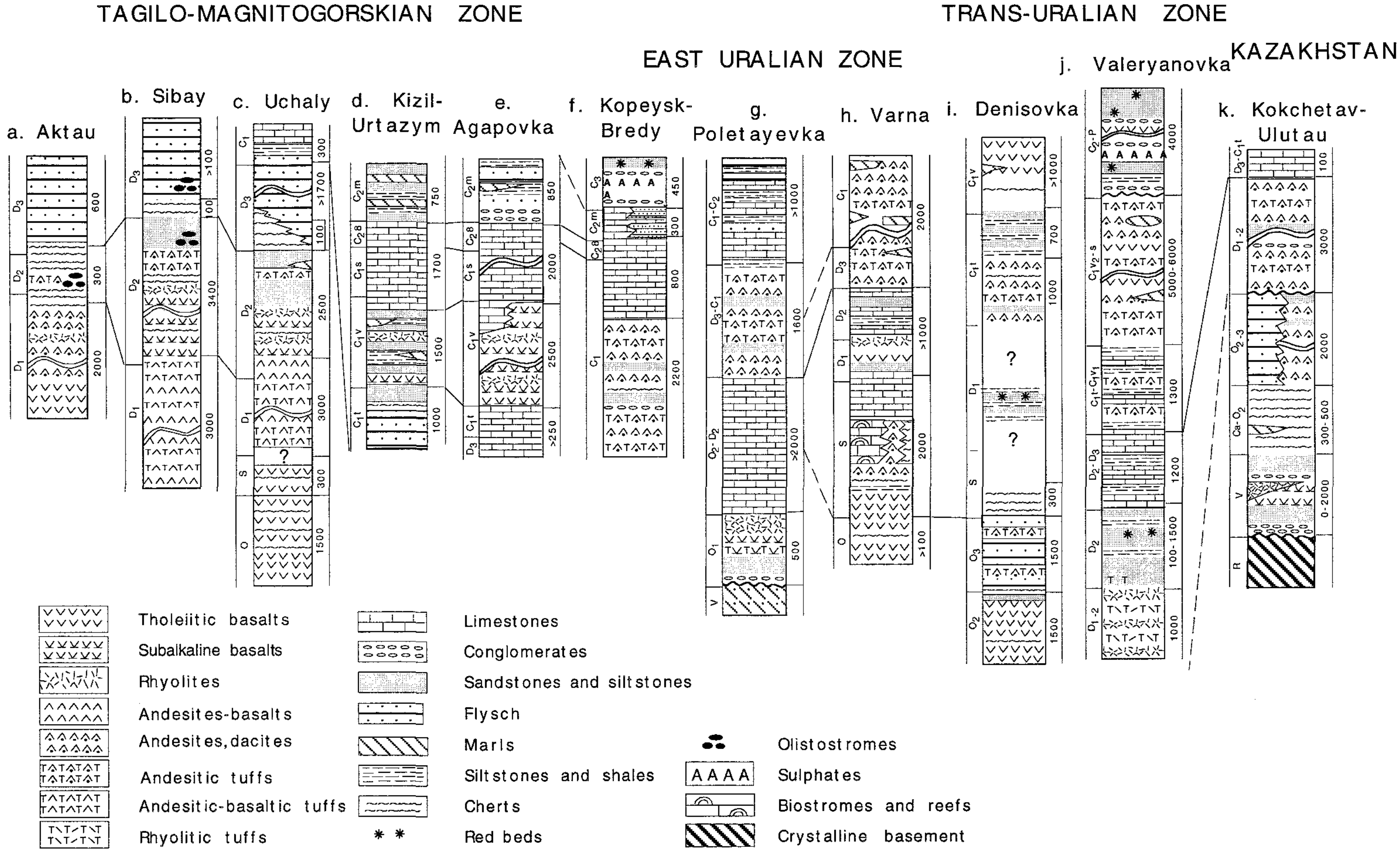


Fig. 14. Schematic correlation of Palaeozoic stratigraphic sections east of the Main Uralian Fault. Compiled after Stratigraficheskiye (1993), Maslov *et al.* (1993) Snachev *etal.* (1994), Puchkov & Ivanov (1985), Chuvashov *et al.* (1984) and Abdulin (1984). The positions of the sections are shown in Fig. 20. Stratigraphic lettering as in Figs 4, 9 and 13.

Yu and Maruun-Keu areas), but more stratigraphic research and isotope dating is needed to make a certain conclusion on their age and nature.

The Tagilo–Magnitogorskian, East Uralian and Transuralian zones belonged to the active margin of the Kazakhstanian (Kazakhstano–Kirgizian) continent (Yazeva *et al.* 1989; Puchkov 1991). They are less uniform compared with the first three zones. What unites them, is a wide development of magmatic complexes, indicators of subduction (Fig. 14). Their geochemical trends show that the subduction zone was dipping beneath the accreting Kazakhstanian continent, to the east in modern coordinates (Yazeva *et al.* 1989; Seravkin *et al.* 1992).

The Main Uralian Fault

The Central Uralian and Tagilo–Magnitogorskian zones are thought to be divided by an east-dipping major suture zone called the Main Uralian Fault (Fig. 4). A considerable part of it is marked by serpentinitic melanges whose matrix records a combination of intense brittle and low-temperature (greenschist) ductile deformation. In some places the melange is replaced by zones of blastomylonites of different metamorphic grade. Blocks in the melanges represent mostly rocks of the hanging wall of the Main Uralian Fault. The most common are ultramafites, gabbros, amphibolites, basalts, cherts and cherty shales of Ordovician, Silurian and Devonian age, Silurian and Devonian limestones, Devonian andesites and dacites, Upper Devonian–Lower Tournaisian greywackes and granitoids of different types. Very typical are low-temperature metasomatic rocks of rodingite type.

The Tagilo–Magnitogorskian zone (Zone 4)

This zone is composed of Palaeozoic complexes of oceanic basins, island arcs, Andean-type belts, flysch troughs covered by shallow-water sediments: limestones and coal-bearing terrigenous sequences (Peyve *et al.* 1977). The ophiolites are widespread (Savelyeva 1987). The volcanic calc-alkaline complexes characteristic of subduction (tuffs, lava basalt and andesite series, as well as their intrusive equivalents) are also well represented (Yazeva *et al.* 1989; Seravkin *et al.* 1992).

The stratigraphy and history of some parts of this zone differ considerably, so that four main subzones, Magnitogorsk, Tagil, Voykar and Schchuchya are established successively (13, 6, 5 and 4 in Fig. 1). The main differences between them are not in the character and composition of the main formations, but mostly in their age. For example, in the Tagil subzone, the ophiolites are Ordovician and the calc-alkaline formations are mostly Silurian. The Devonian is represented by flysch, trachyandesites and shoshonite-type magmatic rocks and the widely developed sedimentary cover of a mature island arc, represented by layered and reef limestones with bauxite deposits. The specific feature of the Tagil subzone is an exemplary development of mafic–ultramafic massifs forming the so-called platinum-bearing belt (Yefimov *et al.* 1993). As for the Magnitogorsk subzone (Fig. 14), the ophiolites range in age from Ordovician to Emsian, the calc-alkaline basalts appear in the Ordovician, but intense calc-alkaline magmatism combined with abundant volcano-terrigenous sedimentation ranges in age from Emsian to Famennian. Flysch sedimentation took place in Famennian–Tournaisian time. Shallow-water limestones and sub-alkaline volcanites of a mature, and probably rifted arc developed in the Viséan–Serpukhovian (Perfilyev 1979; Seravkin *et al.* 1992; Salikhov *et al.* 1993). Massifs of platinum-bearing association are not typical for this subzone.

No Precambrian granitoid and metamorphic rocks outcrop in the Tagilo–Magnitogorskian zone. Their presence at depth is probable as a consequence of a major westward displacement along the Main Uralian Fault, as follows from the interpretations of the geological and geophysical data (Sokolov 1992; Petrov & Puchkov 1994; Figs 4 & 5). The crust of Tagilo–Magnitogorskian zone as a whole is very dense, composed mostly of ultramafic, mafic and intermediate rocks. Derived from the high gravity and magnetic anomalies over it as well as interpretations of many DSS profiles crossing the Urals at different latitudes (Necheukhin *et al.* 1986; Avtoneev *et al.* 1991), crustal thickness is believed to be 45–70 km (Figs 2 & 3). The zone is limited to the east by serpentinite-bearing faults of westward (mostly 20–40°) inclination as is well documented by seismic profiling (Menshikov *et al.* 1983; Sokolov 1992; Fig. 4b). They may be connected with eastward directed backthrusts over the East Uralian zone. The central parts of the Tagilo–Magnitogorskian zone are moderately deformed compared to what can be expected in the centre of a fully fledged foldbelt. There are even very weakly deformed blocks (e.g. area of Podolsk copper-pyritic deposit, Fig. 4c, easternmost part of the profile), the intense dislocations being concentrated in serpentinite melanges, like those of the Main Uralian Fault.

These melange zones are typically tens to hundreds of metres thick (up to several km wide), and are in fact megabreccias containing blocks of dismembered ophiolites, calc-alkaline volcanites, granites, cherts and limestones. Their serpentinite matrix is cut by numerous slickensided surfaces. Taking into account the opposite dip of the melanges across the axis of the Tagilo–Magnitogorskian zone (Fig. 4b; Sokolov 1992) and an evidently considerable tectonic transport along these melanges, it has been proposed that the Tagilo–Magnitogorskian zone was completely allochthonous in character (Kazantsev 1991). The following arguments seem to make this idea invalid.

(1) It has been shown that on the western slopes of the Urals, in spite of folding and thrusting, the primary facies of the passive continental margin with its shelf and bathyal zones are easily restored (Puchkov 1979). It has been shown that the outer border of the shelf zone was rimmed by a stable band of barrier reefs of Late Ordovician, Mid-Silurian and Early–Mid-Devonian age (Antoshkina & Eliseev 1988; Chuvashov & Shuysky 1990). These observations indicate that the edge of the continent was located in this area and only a small part of it (no more than a few tens of kilometres wide) could be thrust below the Main Uralian Fault. Therefore, the platform cannot continue at depth east of the middle of the Tagilo–Magnitogorskian zone or as a part of the East Uralian zone.

(2) Studies undertaken by Khatyanov (1963), Gafarov (1970) and others show that magnetic lineations reflecting the structures of the Precambrian folded basement of the platform can be traced from the western slope of the Urals up to the Main Uralian Fault. The prolongation of these anomalies is not identified in the east as would be the case if the Tagilo–Magnitogorskian zone were a synformal klippe thrust from somewhere in the east.

(3) All deep seismic sounding profiles as well as the presence of a high gravity anomaly over the Tagilo–Magnitogorskian zone suggest that substantial deep structural and compositional crustal changes occur to the west of the Main Uralian Fault (Necheukhin *et al.* 1986, Figs 2 & 3).

(4) Palaeomagnetic data (Svyazhina *et al.* 1992) give evidence of a significant horizontal movement (about 2000km) of the East Mugodzhary block relative to the East Europe in Ordovician–Carboniferous time. In addition, CDP profiling and deep drilling in the Central Uralian zone of the Southern Urals have produced no evidence of the autochthonous Paleozoic platform cover at any depth (Skripiy & Yunusov 1989; Fig. 13).

The idea of a completely allochthonous, exotic character for the Tagilo–Magnitogorskian zone can be rejected due to the presence of a high-amplitude thrust on its western limb and a backthrust along its eastern boundary (Puchkov 1991, 1993; Matte 1995).

The East Uralian zone (Zone 5)

This zone is distinguished by the presence of sialic, microcontinental complexes, fragments of Precambrian continental crust (including the East Mugodzhary, Murzinka–Aduy, Salda, Selyankino blocks; Krasnobayev 1985; Krasnobayev *et al.* 1995; successively 12, 7, 8, 3, SK in Fig. 1). They have distinctive Palaeozoic magmatism and metallogeny (e.g. carbonatites connected with the Selyankino block, Levin 1984) and their own Palaeozoic sedimentary cover, although very poorly preserved and difficult to identify. The sediments of the cover are observed in graben-like depressions of the southern part of the East Mugodzhary block (Southernmost Urals), and also in the Poletayevka and Rezh areas (Middle Urals) and are represented mostly by carbonate, terrigenous and cherty sediments (Puchkov 1993). Volcanic formations are also developed.

In the Poletayevka area (Fig. 14g) Precambrian metasediments are overlain by a Lower–Middle Ordovician, 1500 m thick, rhyolite–basalt series. This in turn is overlain by Middle Ordovician–Middle Devonian carbonate deposits, more than 2000m thick. The Late Devonian–Early Carboniferous is represented by a volcano-sedimentary series that contains andesites and tuffs, up to 1600 m thick. The uppermost part of the section is represented by a Lower–Middle Carboniferous terrigenous-carbonate series (Snachev *et al.* 1994). We interpret this section as a record of a microcontinental block that underwent rifting in the Early–Mid-Ordovician, tectonic quiescence in the Mid-Ordovician–Mid-Devonian and was influenced by a subduction zone in the Late Devonian–Early Carboniferous.

Palaeozoic ophiolitic and island-arc complexes are present in the East Uralian zone as serpentinitic melanges, tectonic klippen and thrust sheets (the largest of them is probably the Denisovka subzone, though its interpretation as a suture cannot be excluded; Puchkov & Ivanov 1985). The East Uralian volcanogenic belt (Koroteev *et al.* 1979; Seravkin *et al.* 1992) is probably allochthonous: on geological maps its southern end looks like a periclinal synform.

Another specific feature of the East Uralian zone is the abundance of granites that align submeridionally to form the 'Main Granitic Axis of the Urals' (Fig. 1). Two main types of granitoids are recognized (Puchkov *et al.* 1986; Fershtater *et al.* 1994): Upper Devonian–Lower Carboniferous tonalite–granodiorites with a calc-alkaline geochemical affinity and Upper Carboniferous–Permian potassium–sodium granites thought to result from partial melting of the collided continental blocks. The magmatism of the Main Granitic Axis of the Urals was also accompanied by Late Palaeozoic zonal metamorphism, due to a thermal influx and deep burial of the East Uralian zone during the late stages of orogenesis (Puchkov 1996).

The Transuralian zone (Zone 6).

This, the easternmost, most poorly exposed and least studied zone, has a rather controversial eastern boundary separating the Uralides from the Kazakstanides (Caledonides). Only Carboniferous and Devonian rocks of ensialic nature are known. The most important are calc-alkaline volcano-plutonic complexes (Fig. 14j). The Devonian sequence consists of: (1) Lower–Middle Devonian volcanogenic units of tuffs and lavas of liparite and dacite composition, up to 1000 m thick; (2) volcano-sedimentary units (Middle Devonian?), represented by continental red-coloured tuffites, polymictic and volcanomictic siltstones and sandstones, 700–1300 m thick; (3) marine shallow-water carbonate-terrigenous series of Givetian–Famennian age, 1200 m thick. The Carboniferous rocks belong to a Valeryanovka marginal volcano-plutonic belt and are comparatively well studied. Here they consist of three series (Chuvashov *et al.* 1984). (1) A Tournaisian–Early Viséan 1200 m unit of shales, siltstones, limestones with subordinate layers of andesites, andesite–basalt porphyrites and tuffs. (2) A mid-Viséan–Serpukhovian 5000–6000 m thick series of basic and intermediate porphyrites, tuffs and lava breccias, with subordinate limestones. The first two series are mostly open-sea shallow-marine in character. (3) Unconformably overlying these is a red-coloured terrigenous continental series composed of conglomerates, sandstones and siltstones with subordinate porphyrites and anhydrites, dated by spores and pollen complexes as Mid-Carboniferous–Permian (Abdulin 1984) and having a thickness of up to 4 km. The volcanites are penetrated by comagmatic intrusions of gabbro–diorites and diorites.

The pre-Mid-Carboniferous rocks are deformed into a series of narrow linear folds with limb dips between 25 and 60°. The overlying molasse-like Upper Palaeozoic redbeds form more gentle synclines and graben-like structures. The zone is limited to the east by the Urkash fault marked by serpentinites (serpentinitic melange?) which may be a suture zone between the Uralides and the Kazakhstanides. There is a deficit of hard data to establish the nature of this boundary precisely. But it is worth mentioning that one of the main differences between the eastern zones of Uralides and the western zones of Kazakhstanides lies in the different age of the main rifting episode preceding the formation of oceanic and marginal complexes (Ordovician in the Urals, Vendian in the Kazakhstanides; Fig. 14).

East of the suggested suture zone, a Devonian volcano-plutonic belt occurs. The thick calc-alkaline series is superimposed on terrigenous-cherty, greywacke and andesite rocks of the Vendian–Late Ordovician complexes typical for the Kazakhstanian 'Caledonides'. These volcano-plutonic belts are probably fragments of a longer and wider zone, connected with the Chatkal–Naryn belt of the South Tien-Shan.

The present-day crust of the East Uralian and Transuralian zones is 38–42 km thick and composed of rocks lighter than the Tagilo–Magnitogorskian zone (Necheukhin *et al.* 1986; Avtoneev *et al.* 1991; Figs 2 & 3). The crust of the Urals as a whole records thrusting and stacking of differently composed tectonic units along faults whose inclination changes with depth, creating several levels of listric faults. This is documented by seismic reflection and refraction data and complicates the relationships between deep and shallow structures of the Uralian megazones which involve structural detachments between various deep horizons, density inversions in the crust and close horizontal connections (even interfingering) between adjacent megazones, however contrasting their character at the surface (Puchkov & Svetlakova 1993).

Relicts of the Pre-Uralian orogen

In the Central Uralian zone Upper Proterozoic (Riphean and Vendian) deformed and metamorphosed rocks are exposed. They belong to the 'Douralides' tectonic complex of Kheraskov (1967). The English equivalent of the term can be Pre-Uralides because they form the basement of the Palaeozoic complex of the 'Uralides'. They have also been called Timanides, because the basement of the Timan Range was an important part of this orogen. Crystalline com-

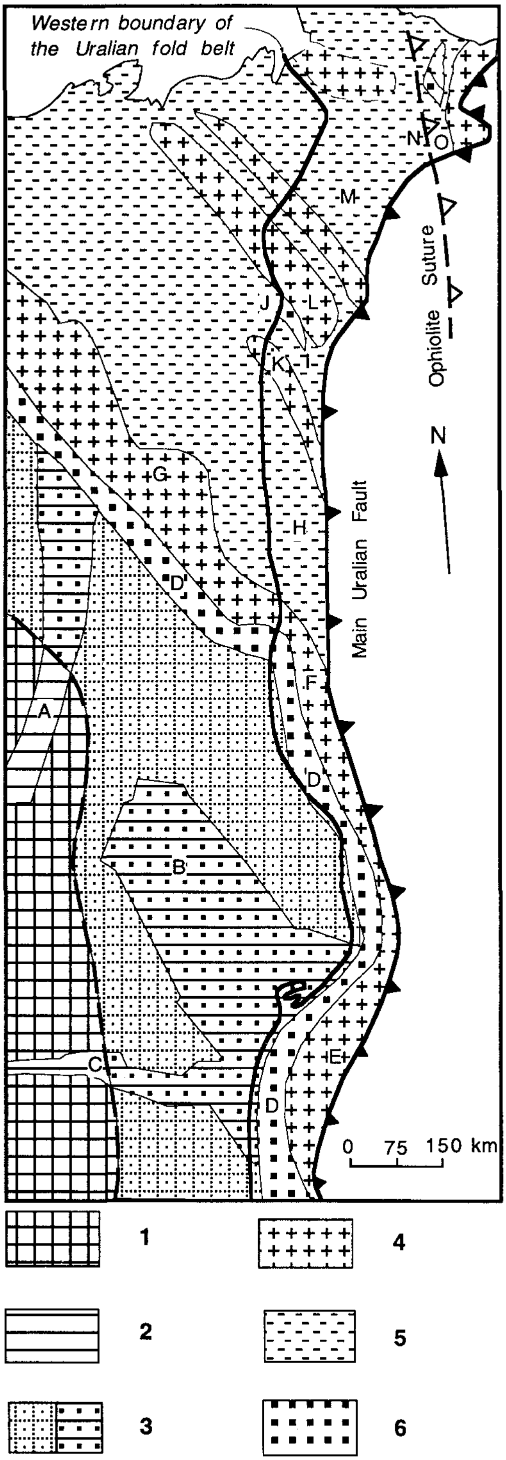


Fig. 15. Schematic tectonic zonation of the Pre–Late Proterozoic basement structures of the East European platform traced to the western slope of the Urals 1–3: Pre-Riphean craton; 1, Uplifted Archaean–Early Proterozoic blocks; 2, Riphean aulacogens; 3, first two structural zones overlain by a Vendian platform cover. 4–7: Pre-Uralides; 4, anticlinoria; 5, synclinoria; 6, foredeep and intermontane depressions. The letters in the figure correspond to those discussed in the text. The position is shown on Fig. 23.

plexes of Archaean–Early Proterozoic age are exposed as small isolated regions among the Pre-Uralides (Taratash complex of the Middle Urals and some other metamorphic terranes of granulite and amphibolite facies), separated from the Late Proterozoic (Riphean) complexes by faults.

General features of the Pre-Riphean structures in the Central Uralian zone cannot be reliably deciphered. However, like the Late Proterozoic structures, they can be traced from the Central Urals to the basement of the northeastern part of the East European platform, using geophysical and geological data (Gafarov 1970; Puchkov 1975; Fig. 15).

By the end of the Proterozoic, these regions belonged to a single continent. In its southern part, an Archaean–Lower Proterozoic craton was subdivided into older cores (Belomorides) and younger foldbelts (Karelides). The cratonic basement of the Volga–Ural region is complicated by three Riphean graben-like structures: the Kazhim, Kaltasy and Sernovodsk–Abdulino aulacogens (A, B, C respectively on Fig. 15). They are up to 8–10 km deep (Romanov & Isherskaya 1994); continue in the western part of the Bashkirian anticlinorium of the Urals, and are overlain by up to 2 km of Vendian terrigenous sediments that form the lowermost member of the platform cover proper.

The intensity of tectonism of the Late Proterozoic rocks increases to the east and north. By Vendian times, a vast collisional orogen had formed at the western slope of the Urals (including the Central Uralian zone), in the Timan Range and Timan–Pechora Basin (Getsen 1991; Puchkov 1993), with the following structural elements shown on Fig. 15 (Puchkov 1975, 1993): a foredeep filled with Late Vendian molasse (D, Fig. 15); marginal anticlinoria: East Bashkirian (E), Kvarkush (F), and Timan (G); Vishera–Ilych–Chiksha (H) and Denisovka–Sablya (I) synclinoria, Man'–Khambo (K) and Kolva–Khobeiz (L) anticlinoria, the Laptopay intermontane depression (J), the Lemyu–

Khoreyver undifferentiated zone (M), the Yengane–Pe ophiolite suture (N), the Oche–Nyrd subduction-related volcanic zone (O) and the Marunkeu–Kharbey anticlinorium (P). The pre-Uralian zones (Fig. 15) have different trends compared to the overlying Uralides (only in the Southern Urals do they coincide to some extent).

The Riphean–Early Vendian history of the Pre-Uralian orogen is characterized by the development of wide troughs on a continental crust due to epicontinental rifting. Extension was accompanied in some places by the formation of sub-alkaline basalts or a rhyolite–basalt series of continental affinities (e.g. Goldin *et al.* 1973; Parnachev 1981; Parnachev *et al.* 1981; Getsen *et al.* 1987; Ivanov 1987). Among the sedimentary complexes of the Pre-Uralides, shallow-water quartzites, subarkoses, arkoses, bioherm algal limestones and dolomites are predominant. Poorly studied formations with ophiolitic and calc-alkaline affinities (Rumyantseva 1984; Puchkov 1993) are found only in the Polar Urals. Some authors (e.g. Ivanov 1987) discard part of these data as well as the presence of Pre-Uralian folding and orogenesis, in contrast to many earlier and some later researchers (e.g. Shatsky 1963; Perfilyev 1968; Gafarov 1970; Puchkov 1975, 1993; Getsen 1991).

The Pre-Uralian orogen was formed as a result of a Late Vendian (approx. 630–570 Ma) continental collision (Puchkov 1993). The orogeny was characterized by (a) deformation reflected in an unconformity at the base of the Ordovician sequence; (b) Barrovian metamorphism and S-type magmatism connected with thermal domes, partially distorted by later deformations, both Late Vendian and Late Palaeozoic; (c) formation of a foredeep filled with Late Vendian polymictic and arkosic terrigenous sediments, including conglomerates and (to the south of the Timan Range) evaporites. Rather small intramontane basins filled with molasse of Vendian age are present in the northern Urals (Puchkov 1975). In addition to lithologies of the Riphean complexes of the Bashkirian anticlinorium (quartzites, crystalline schists, dolomites, granites, syenites), Vendian conglomerates of the Southern Urals also contain pebbles of red jasper which may have originated from Riphean–Early Vendian deep oceanic sediments which are either not now at the surface (existed in overthrusts and now eroded) or are as yet undated.

Correlation of the Pre-Uralides with orogenic events in areas outside the Urals and Timan has not been thoroughly investigated. Of the adjacent areas where an orogeny can be tentatively correlated to the Pre-Uralides, two can be named: (1) Spitzbergen, where a pre-Mid-Ordovician unconformity is described, with metamorphic basement rocks, dated by the K–Ar method at 556, 584 and 621 Ma (Ohta *et al.* 1986) and (2) Taymyr, where collisional granites and amphibolites are dated at 560–625 Ma (Vernikovsky 1995).

The Pre-Uralian orogen was previously erroneously correlated with the Baykalides (e.g. Shatsky 1963). In fact, its origin appears to be unrelated to the Late Precambrian tectonic events of the Baykal area of Siberia. The time of formation of the Pre-Uralides is close to that of the Cadomian foldbelt of northern Europe (Puchkov 1988a). Recent global paleotectonic reconstructions for the Vendian and Early Cambrian time (Nance & Murphy 1994; McKerrow 1994) ignore the Pre-Uralides which should be placed very close to fragments of the Cadomian–Avalonian orogen (Fig. 16). It is probable that the Pre-Uralides were an integral part of a great Late Precambrian orogen within the Rodinia supercontinent.

In Early Palaeozoic time Rodinia was affected by intense rifting and one of the branches of the rift system ran parallel to the later Main Uralian Fault. The event led to the formation of the Palaeo-Uralian ocean and the passive margin of the East European continent. The continental rifting in the latest Cambrian and earliest Ordovician (Tremadoc) was accompanied by the formation of 'graben complexes' usually represented by a terrigenous series of variable thickness. They are accompanied by sub-alkaline and alkaline basalts and rhyolites, picrite porphyrites and tuffs (Goldin & Puchkov 1978; Ivanov *et al.* 1986; Dembovskiy *et al.* 1990). The presence of the Early Ordovician (Arenig) and younger (up to Eifelian) ophiolites in the Tagilo–Magnitogorskian zone and in some thrust sheets in the West Uralian zone reliably date the Palaeo-Uralian ocean (Puchkov 1993).

The tectonic nature of the Uralian Cambrian

The Cambrian in the Urals is poorly developed. In some places the latest Cambrian, represented by coarse terrigenous sediments and rift volcanics conformably underlies Lower Ordovician quartzites and quartz sandstones which are widely developed in the western slope of the Urals. The Mid-Cambrian is not known, probably due to general uplift and erosion, which affected the eastern part of the East European platform at this time. Massive, reef limestones

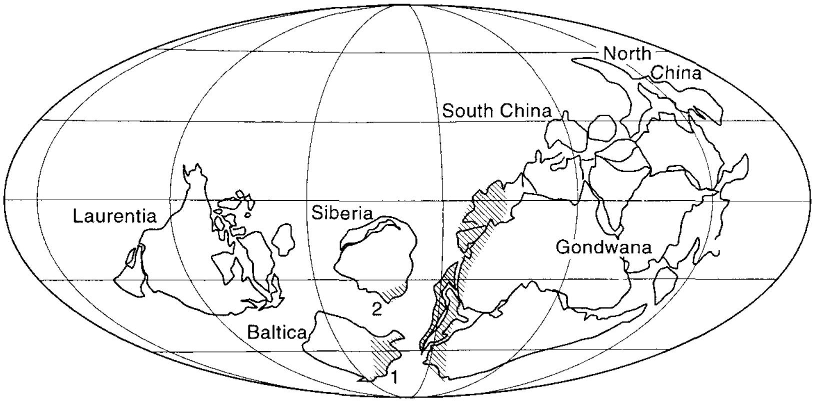


Fig. 16. Palinspastic reconstruction of continents in the Cambrian (McKerrow 1994, modified). Hatched areas are the Late Proterozoic orogens; 1, Pre-Uralides (Timanides), and 2, Taymyr are added to the reconstruction.

with archaeocyatids and algae of Early Cambrian age are known in two restricted areas: the Sakmarian allochthon (14, Fig. 1) and the Troitsk subzone (10, Fig. 1). In the Sakmarian subzone, the limestones constitute part of two 'suites': a lower one consisting of sandstones with subordinate tuffites and basalts and an upper one composed mostly of basalts, volcanic breccias and cherts. The thickness of these units varies between 600 and 1700 m. Limestones are encountered in all parts of the section, and their nature is a subject of continuing discussion. Some geologists believe they are *'in situ'* bioherms, others that they are biohermal olistoliths in sandstones and xenoliths in basalts. As such, they provide only the lower age limit of the suites. The only reliable *'in situ'* occurrence of conodonts in cherts dates the rocks, which enclose Lower Cambrian limestones, as Late Cambrian (Puchkov 1993). The Late Cambrian age and the unusually high Mn content of the volcanic rocks in the section suggests that the sequence records epicontinental rifting, the precursor of the Palaeo-Uralian ocean.

Development of the Palaeo-Uralian ocean

The main stages the Palaeo-Uralian ocean in the Palaeozoic are shown in Fig. 17 (see also Puchkov 1991, 1993). The most important features are: early development of an island arc and accretion against the Kazakhstano–Kirgizian continent, itself a collage of microcontinents and island arcs. The subduction zone was dipping to the east (in modern coordinates), under the Kazakhstano–Kirgizian continent. The sense of dip is deduced from the analysis of geochemical trends of calc-alkaline magmatism (Yazeva *et al.* 1989; Seravkin *et al.* 1992). It is also supported by the fact that the East-European/Laurussia margin of the Palaeo-Uralian ocean was passive (Puchkov 1979; Fig. 10).

The Palaeozoic continental collision in the Urals

The Uralian orogeny resulted from collision of the active and passive margins. Prior to collision, some minor collisions of microcontinent–island arc type and microcontinent–continent type took place throughout the Ordovician, Silurian and Devonian along the margin of the Kazakhstano–Kirgizian continent. The convergence of plates whose margins remain almost parallel for a long time is an exception. Margins of colliding continents often have uneven, indented outlines, which can cause major differences in structural development along orogens. Many researchers have considered the role of plate margin geometry and oblique collision in their analysis of Phanerozoic and Precambrian foldbelts, (e.g. Glazner 1991; Lyberis *et al.* 1992; Russo & Speed 1992; Ryan & Coleman 1992). Observations relevant to this problem have been made in the Urals too, although not in a systematic way.

Palaeomagnetic data (Svyazhina *et al.* 1992) show that beginning in the Ordovician, the East Mugodzhary and Kokchetav continental blocks and intervening Denisovka (primarily oceanic) block (their position is shown on Fig. 19) moved along similar trajectories and the scale of their presumed convergence and collision (Puchkov 1991) was too small to be seen by the palaeomagnetic method. These blocks that belonged to the

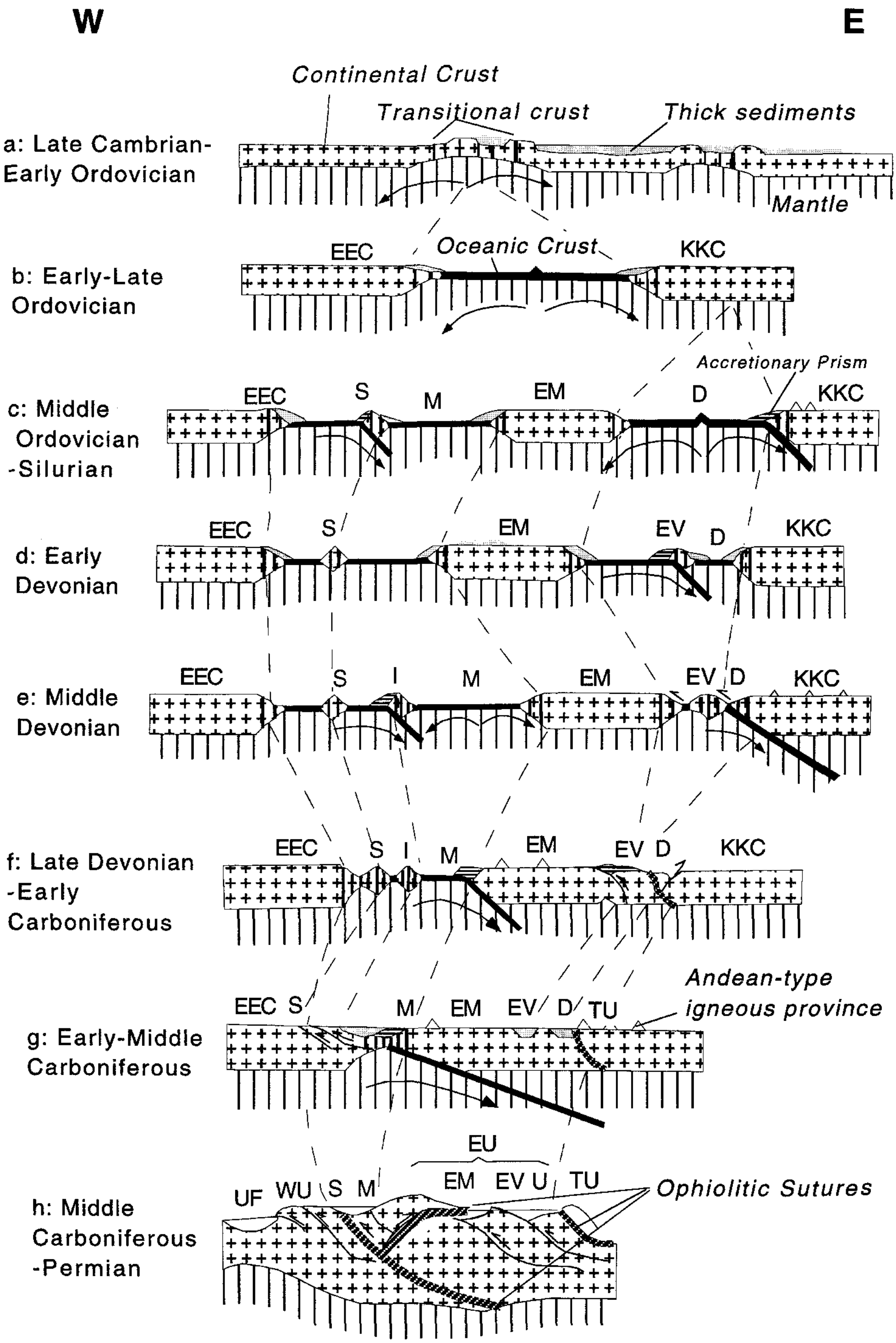


Fig. 17. Palinspastic profiles through the Southern Urals during the successive stages of its development in the Palaeozoic. EEC, East European continent; KKC, Kazakhstano–Kirgizian continent; S, Sakmara island arc; M, Magnitogorsk oceanic basin; EM, East Mugodzhary microcontinent; D, Denisovka oceanic basin; EV,East Uralian volcanic subzone; WU, West Uralian zone; EU East Uralian zone; TU, Transuralian zone.

Palaeozoic Kazakhstano–Kirgizian continent were situated: (1) at the same latitude as the territory of Kola Peninsula in the Ordovician, (2) opposite to the Middle Urals in the Late Carboniferous and (3) in a relative position close to the modern one in the Permian. According to these palaeomagnetic data, we must accept a non-cylindrical convergence of the two continents during their Palaeozoic history, including the period of their collision. Geological data strongly support this point.

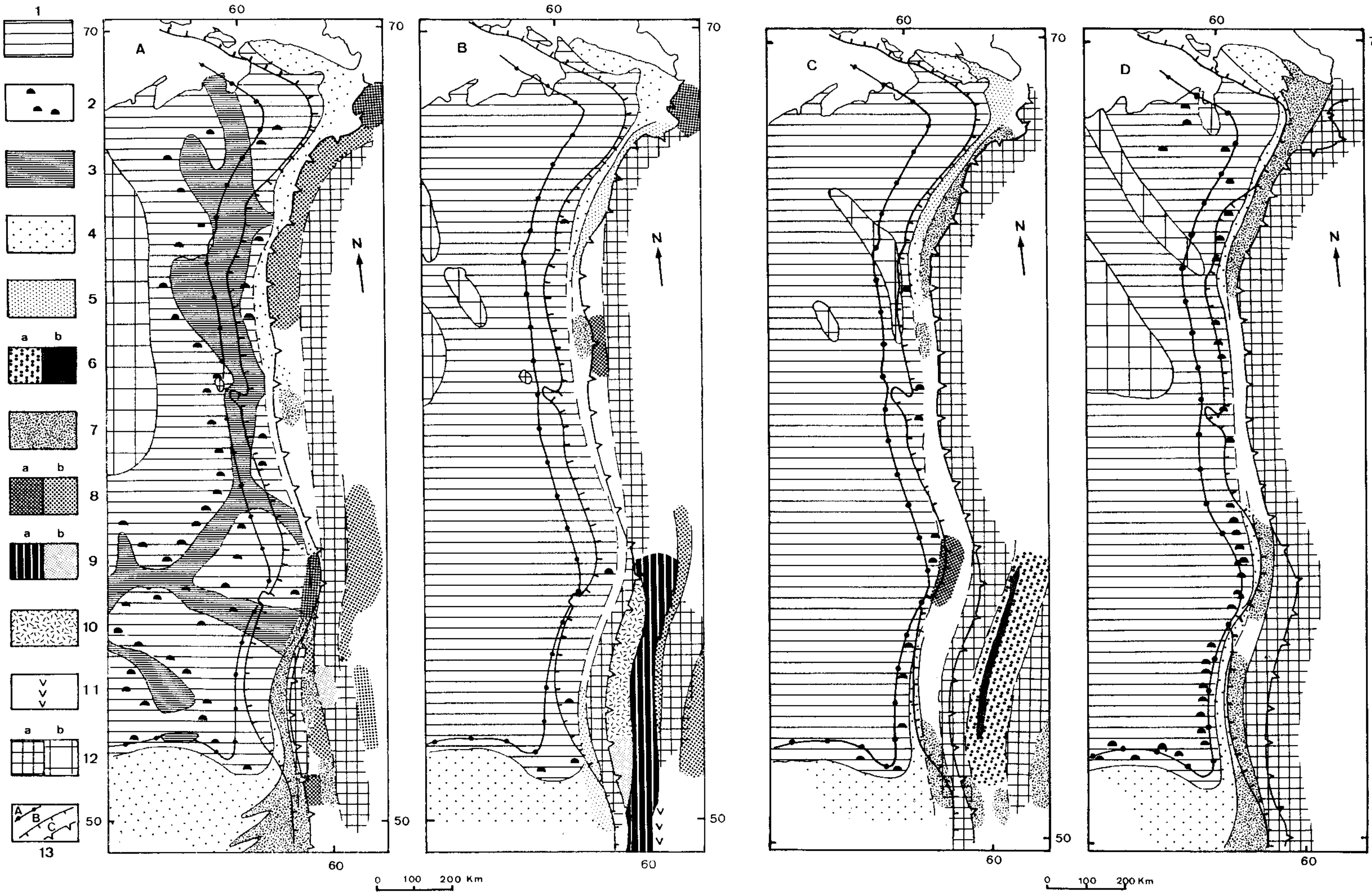
The first sign of collision between the Kasakhstanian active margin and the East European passive margin is found in the Upper Frasnian in the Southern Urals. In the Sakmara subzone and the eastern limb of the Zilair synform the Zilair flysch of eastern provenance conformably overlies Eginda and Ibragimovo cherts dated as Frasnian and interpreted as bathyal sediments of the East European passive margin (Puchkov 1979). This flysch was thought to be Famennian–Tournaisian in age, although Chibrikova & Olli (1987) reported Late Frasnian spores and pollens and the Latest Frasnian ages for chert intercalations close to the bottom of the flysch. In any case, the middle of the Late Devonian may be chosen formally as the beginning of collision *(sensu lato),* when the continental margins came into close proximity.

During the Famennian, Early Carboniferous and most of the early Mid-Carboniferous subduction was still active with the formation of andesite, trachyandesite–rhyolite, monzonite–granosyenite (shoshonite), tonalite–granodiorite formations in the east (Ivanov *et al.* 1986; Puchkov *et al.* 1986; Salikhov *et al.* 1993 and others). These processes at the colliding margins can be compared to the modern collision between Australia and Southeastern Asia where the Sunda arc may play the role of a damper before the main collision. According to this model, applied to the Palaeozoic Urals, two stages in the collision can be recognized. The first is the transitional stage, termed a soft collision (Late Devonian–Early Carboniferous), when the continental margins came in contact, but the relict slab of the oceanic lithosphere was still being subducted, undergoing partial melting and producing calc-alkaline volcanites. The type of deformation associated with this stage is difficult to establish. The first thrusts carrying oceanic crust onto the former passive margin (Bardym, Kraka and Sakmara nappes) may have developed by this time. These thrust sheets were subsequently folded, overlie rocks no younger than the Late Devonian Zilair flysch and contain no rocks with proved age younger than Famennian. If so, the crust may have thickened slightly as a result of thrust stacking, but it was not so thick that it produced a high land mass. The second stage, termed a rigid collision (collision *sensu stricto)* is dated as Mid-Carboniferous–Late Permian and produced intense stacking of thrust sheets (involving Carboniferous and Permian rocks), growth of the Uralian foldbelt and a mountain range with a mountain root, generation of anatectic granites of the Main Granitic Axis (Fig. 1; Fershtater *et al.* 1994), and development of the Uralian foredeep and intermontane basins.

The Famennian–Tournaisian flysch trough (Fig. 18a) in the southernmost Western Urals has a distinct deep-water character. The thick Famennian graywacke series graded westward into the condensed Kiya unit of marls, cherts and bituminous shales (Puchkov & Ivanov 1987). The greywacke with eastern provenance did not reach the shelf zone of the passive continental margin until the deep-water trough, the relict of the bathyal zone, was filled. Therefore, the trough acted as a sedimentary trap for the terrigenous sediments from the eastern Uralian Zones. The time when this trap was filled is difficult to define and was certainly different at different latitudes. Keller (1949) has shown that in the northwestern part of the Zilair synform, Visean greywackes overlie shallow-water shelf sediments of Famennian and Tournaisian age. Therefore the initial deep-water trough was filled no later than Tournaisian. In contrast, in the Ufimian amphitheatre of the Middle Urals (1, Fig. 1), where the passive margin had a distinct 'promontory', Famennian greywackes are reported to overlie immediately the Frasnian shelf limestones (Smirnov & Smirnova 1961, 1967; Kamaletdinov 1974). There are two explanations for the absence of bathyal sediments under the greywacke series. Either the collision against the 'promontory' was more rigid and the deep-water trough between the margins was rapidly closed, or the graywackes are thrust upon the shelf sediments.

Further to the north, the Famennian–Tournaisian graywacke is present in the Tagilo–Magnitogorskian zone, but nowhere overlies the bathyal sediments of the East European continental margin (Fig. 18a). The disappearance of the initial flysch trough was followed by the formation of the Uralian foredeep which migrated westward across the continental shelf. At the same time a considerable influx of terrigenous material from the east took place. Therefore, the margins of the continents first came in contact only in the south of the Urals.

In the Southern Urals the flysch trough disappeared in the Viséan, and probably earlier



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in the Middle Urals. But during most of the Late Tournaisian, Viséan, Serpukhovian and Early Bashkirian the influx of terrigenous material was neither abundant, nor constant, being interrupted by periods of accumulation of pelagic limestones and cherts (Kuruil and Bukharcha suites in the west of the Zilair synform, Keller 1949; modern data on their ages given by Sinitsina *et al.* 1984). Only later in the Mid- and Late Carboniferous when rigid collision started in the Southern Urals, was terrigenous sedimentation intensified. A series of sedimentary facies belts typical of a foredeep was established over the shelf sediments of the former continental margin. Coarse terrigenous sediments identified as molasse (Chuvashov & Nairn 1993), were followed by flysch and olistostromes, then by condensed basinal sediments, carbonate reefs, and finally shallow-water interbedded limestones and dolomites (Fig. 7). Such a facies series existed in the southernmost Urals since the Mid-Carboniferous, in the Middle Urals, probably since the Late Carboniferous. In the north the complete series was established in the Early Permian (Fig. 18b, c & d). The facies belts migrated to the west, so that the older and easternmost facies were reworked by fold-and-thrust belt structures to the rear of the foredeep (Nalivkin 1949 ; Khvorova 1961; Chuvashov & Dyupina 1973). The Uralian foredeep developed in the Southern Urals from the Mid-Carboniferous. The Carboniferous facies, typical for the foredeep, were later deformed and became part of the West Uralian zone, and the structure of the current foredeep was established only in Permian time.

A comparable transition from residual trough in the bathyal zone of the passive continental margin to a foredeep migrating westward onto the shelf of the margin, has been established in the Lemva zone of the Polar Urals, (Yeliseev, 1973; Puchkov, 1979, compare again Fig. 10, a and b) where analogous events took place later than in the Southern Urals. The appearance of greywacke flysch in the eastern side of the residual bathyal trough is dated as Okian–Serpukhovian (latest Early Carboniferous) time; the trough was being filled by flysch during the Mid-and Late Carboniferous; terrigenous sediments of the eastern influx appeared on the shelf only in the Early Permian. Conversely, in Kungurian (latest Early Permian) time the terrigenous influx, reflecting the intensity of collision, was at its highest in the Polar Urals, where a thick terrigenous coal-bearing series was formed. In more southern regions evaporites were at this time predominant, conditioned by both climatic variations and low terrigenous influx.

Such diachronism of events is connected with a shift of the collisional process along the Urals' strike. The shift was gradual and continuous, which can be illustrated by a series of simplified structural-paleogeographic schemes for the Late Devonian–Early Permian period (Fig. 18). One can see that the first appearance of greywacke in the corresponding structural zones of the western slope of the Urals became progressively younger to the north. The facies boundaries cut the main structural boundaries of the western slope of the Urals at a very acute angle (2–4°) and move with time not only from east to west, but from south to north. The terrigenous influx became more intense in the north while simultaneously getting weaker in the south. At the eastern margin of the Pricaspian Basin (Fig. 19a) this influx reaches a maximum intensity in Zilair (Famennian–Early Carboniferous) time (Volozh 1991). It was the time when the South Emba branch of the Variscides (Fig. 19), connecting the Urals with

Fig. 18. Schematic distribution of lithofacies in the Urals and adjacent areas, (a) End of the Devonian–beginning of the Carboniferous, (b) Early Carboniferous (Viséan and Serpukhovian time). (c) Mid- and greater part of the Late Carboniferous, (d) End of Carboniferous and beginning of Permian. Symbols: 1, shallow-water shelf sediments (mostly layered carbonates); in the Early–Mid-Viséan. mostly terrigenous sediments with oligomyctic sandstones and coals. 2, reefal massifs and bioherms; 3, comparatively deep-water (domanikoid) basinal facies, mostly shales and marls, developed in the axial parts of the Kama–Kinel trough system; 4, deep-water, bathyal facies: pelagic limestones, cherts, shales; 5, the same, alternating with greywacke or overlain by them. 6, shallow water limestones changing upsection to flysch near uplifts; (a) Late Carboniferous sediments are absent, (b) Late Carboniferous sediments are present; 7, mostly terrigenous sediments of the Uralian provenance (purely terrigenous flysch or tuffaceous-terrigenous turbidites; also molasse for the later stages of development). 8a, terrigenous sediments of the Uralian provenance, alternating with shelf complexes or overlying them; 8b, calc-alkaline volcanics of the subduction zone and accompanying terrigenous rocks; 9a), terrigenous sediments of a local influx intercalated with shallow-water limestones; ab, pure shallow-water limestones. 10-clastic rocks and limestones, associated with trachyrhyolite–basalt volcanics. 11, tholeiitic basalts of the Irgiz zone. 12, uplifts, a, intense, b, weak, subsequently eroded; 13a, western boundary of the Pre-Uralian foredeep prolonged by a northern boundary of the Pricaspian basin; 13b, western boundary of the West Uralian megazone; 13c, Main Uralian Fault.

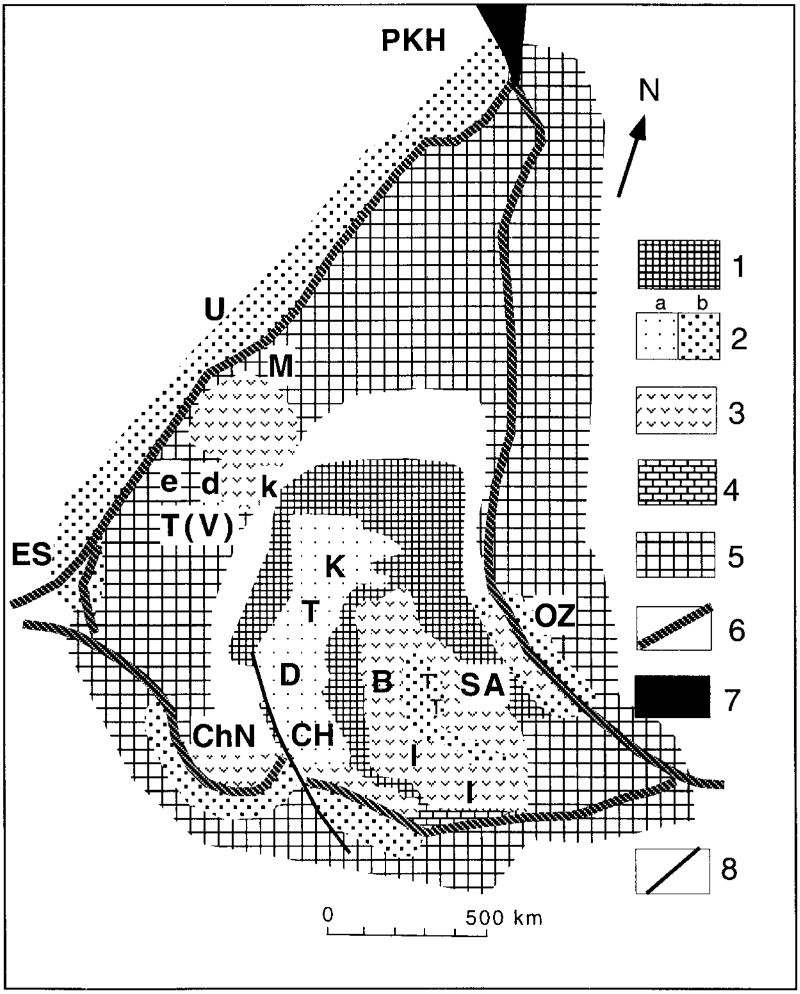

Fig. 19. Zonation of the Kazakhstano–Kirgizian continent in the Late Paleozoic (stage of 'rigid' collision) (Puchkov 1991, modified). 1, Eroded Middle Carboniferous–Permian internal rises; 2, terrigenous sediments, a, flysch and molasse, b, lagoon tuff-terrigenous deposits; 3, Volcano-plutonic complexes; 4, carbonate deposits; 5, Late Carboniferous–Permian orogenic rises connected with collision; 6, suture zones, former boundaries of collided continents/microcontinents; 7, supposed relict oceanic basin; 8, -faults. Structural zone M, Magnitogorsk; T (V), Turgay (Valerianovka); ChN, Chatkalo–Naryn; K, Karaganda; T, Tengiz; D, Dzhezkazgan; CH, Chuya; B, Balkhash; I, Ili; SA, Sayak; OZ, Ob-Zaysan; PKH, Pay-Khoy; U, Uralian foredeep; ES, South Emba; structural subzones: e, East Mugodzhary; d, Denisovka; k, Kokchetav

Greater Caucasus, was active; in the north the peak activity was in Kungurian time.

This mode of Palaeozoic collision in the Urals was complicated by the uneven outline of the passive margin, with a promontory in the Middle Urals, called the Ufimian amphitheatre (1 in Fig. 1). The promontory may have acted as a pivot around which the Kazakhstanian continent rotated several degrees counter-clockwise. Such a rotation, which probably occurred during waning subduction, could result in the formation of local tensional structures in the upper levels of the lithosphere. In fact, this time (mostly Viséan–Early Bashkirian, immediately preceding rigid collision) was characterized in the Southern Urals by the formation of sedimentary and magmatic complexes atypical of collision or subduction: extensively developed shelf carbonates, mantle-derived gabbro–granite and sub-alkaline trachyrhyolite–basalt magmatic associations, layered gabbro–diabase intrusions of trapp affinities, parallel diabase dykes and

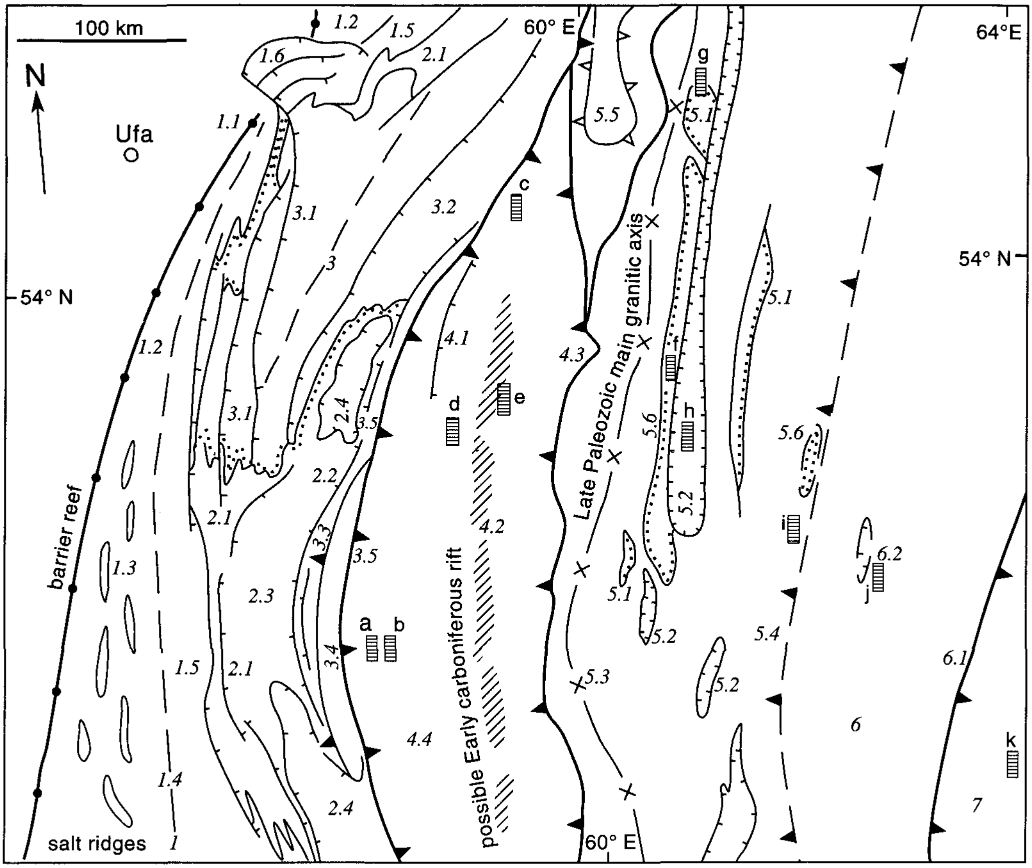

Fig. 20. Most important structures of the Uralian orogen, connected with the Late Paleozoic intracontinental collision (located on Fig. 23). Decorated lines, thrusts; undecorated lines, boundaries of structural subzones. Heavy lines with black triangles, suture zones marked by serpentinitic melanges. Lines accentuated with points, unconformity between Proterozoic and Palaeozoic complexes. The suggested Early Carboniferous rift zone is marked by mantle-derived basalt–trachyrhyolite and gabbro–granite complexes, a–k, Palaeozoic stratigraphic sections of Fig. 14. Numbers in italic are explained in the text. In 5.5: Late Palaeozoic thermal dome characterized by a Barrovian metamorphism.

tholeiitic pillow basalts of the Irgiz zone (Ivanov *et al.* 1984; Frolova & Burikova 1977; Salikhov *et al.* 1993; Fershtater & Bea 1993).

The onset of a rigid collision in the eastern zones of the Southern Urals can be dated reliably enough as the beginning of the Moscowian. All manifestations of subduction related and rifting volcanism had stopped, and carbonate sedimentation began to be progressively substituted by terrigenous deposition; flysch troughs of NNE strike are thought to have existed east of the Main Uralian Fault by the end of the Middle Carboniferous (Chuvashov *et al.* 1984; Chuvashov & Puchkov 1990). Different opinions have been expressed about the presence of the Late Carboniferous and Permian in the eastern zones of the Urals. According to Chuvashov *et al.* (1984) sediments of this age are practically absent. However, in later publications (Abdulin 1984; All-Russian Stratigraphic Committee 1993) one can recognize some relicts of intermontane basins filled with Late Carboniferous and even Permian molasse (red-coloured conglomerates and sandstones with flora remains and anhydrite layers) preserved in the Southern Urals (Figs 14f, g & 20). We have shown the relicts of these intermontane basins in the east of the Urals (Fig. 20, structures numbered 5.6 and 6.2), but only conditionally, taking into account the existing controversy.

The Uralian collision started early in the south, and its intensity varied much along the length of the orogen until the Late Permian, shifting wave-like to the north. By the beginning

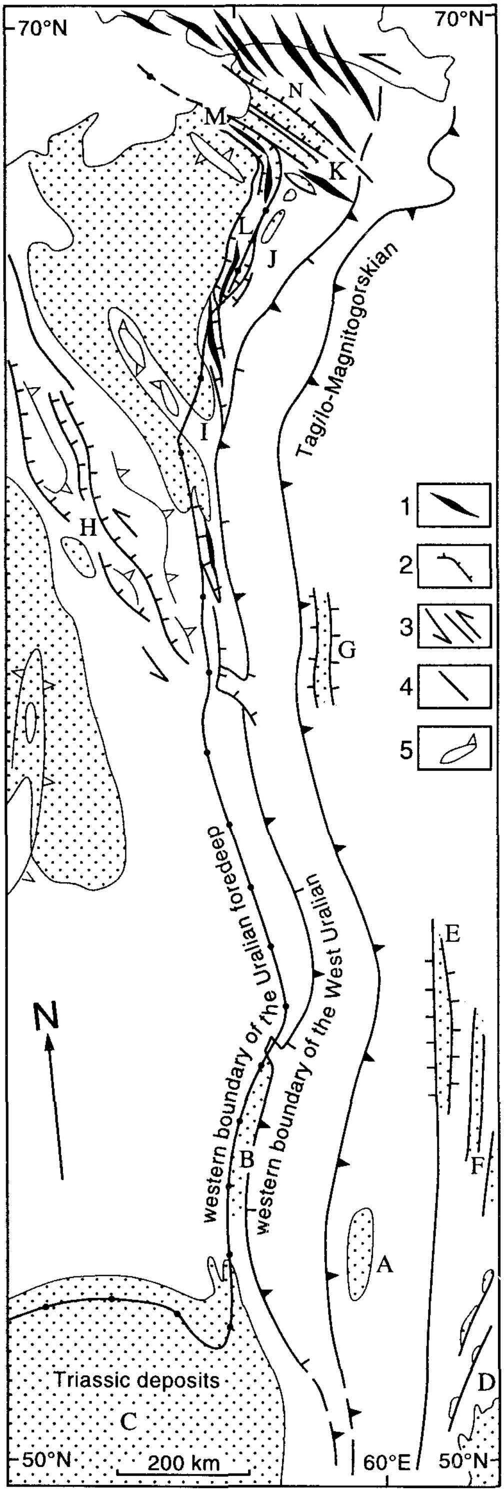

Fig. 21. Old Cimmerian structures in the Urals and adjacent areas compared with the structural boundaries of Uralian Orogen (Variscides). 1, Fold-and-thrust dislocations; 2, overthrusts; 3, wrench faults; 4, undefined faults; 5, gentle, smooth anticlines and flexures of platform type. Letters are explained in the text. Same location as Fig. 18 in Fig. 23.

of the Late Permian the intensity seems to have become more or less equal in all parts of the orogen (oblique collision changed for a time to a cylindrical one). By the end of the Permian, the orogeny was least intense in the east of the Southern Urals, where short ingressions of the Tethys-connected seas were registered (Chuvashov *et al.* 1984).

It is worthwhile noting that the Late Palaeozoic orogenic processes affected areas much wider than the Urals and enclosed the former Kazakhstano–Kirgizian and Siberian continents: wide intermontane basins were formed in Kazakhstan by this time (Fig. 19).

Mesozoic tectonic deformations

The uneven character of the collision was manifested again in the Mid-Jurassic, the Old Cimmerian stage of the region. The Palaeozoic and Old Cimmerian stages were separated by a period of a comparative quiescence with a dissipated rifting episode at the Palaeozoic–Mesozoic boundary, when the territory became a marginal part of the gigantic magmatic trapp province of Siberia.

The Old Cimmerian fold and thrust deformation in the Urals is a comparatively weak, intraplate shortening. Further to the north, in the Pay-Khoy and Novaya Zemlya this deformation was more intense and led to the formation of the Pay-Khoy–Novozemelian foldbelt which did not exist earlier as shown by palaeographic data, pre-Mid-Jurassic structural unconformities and isotopic dates (Chermnykh 1972; Korago *et al.* 1989; Rasulov 1982; Yudin 1994). This foldbelt resulted from direct convergence between the East European and Siberian continents (the structures of the Kazakhstanian continent are not traced so far to the north under the cover of the West Siberian plate, Fig. 19). Although the continents were, by Mesozoic time, integral parts of Pangaea, they were still loose enough to change their relative positions along a system of sinistral and subordinate dextral wrench faults (the directions of movements along these faults are shown in Fig. 21).

Comparison of the structures in areas where Triassic sediments are preserved (Fig. 21), gives

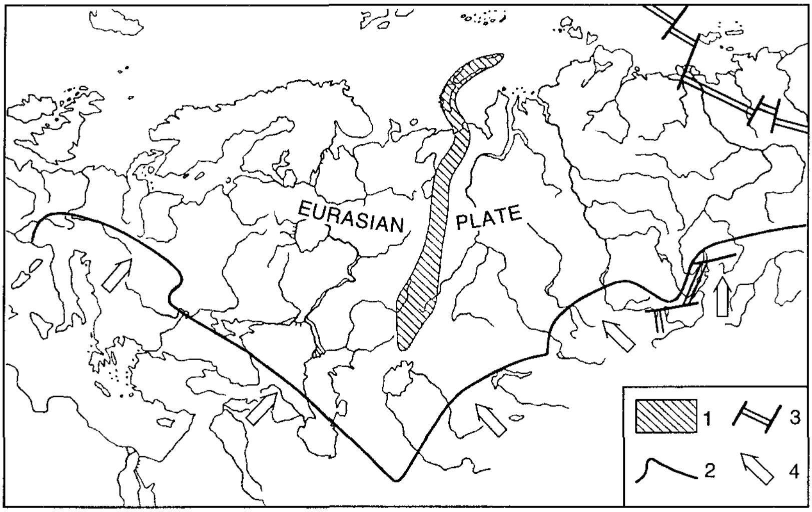

Fig. 22. Position of the Urals mountains in the Eurasian plate with respect to plate margins (Puchkov, 1988). 1, Neotectonic orogen of the Urals mountains; 2 & 3. margins of the Eurasian plate: 2, convergent; 3, divergent. 4, main directions of forces acting at the convergent margin of the Eurasian plate.

some important details concerning the changes in style and intensity of the Old Cimmerian deformations from south to north and west to east. In the Southern Urals Triassic terrigenous coal-bearing sediments of the Orsk basin (Fig. 21 a) and coarse terrigenous sediments of the Uralian foredeep (Fig. 21b) are very thin (up to tens of metres) and practically undeformed (Ozhiganov 1964). In the Pricaspian depression (Fig. 21 c), where a transition from continental to marine sediments occurred, salt domes are developed, but compressional structures (folds and thrusts) are absent. Immediately to the east of the Southern Urals, in the Turgay depression (Fig. 21d), the Triassic–Early Jurassic sequences are developed in linear graben-like depressions and consist of two series, the lower composed of trapp volcanics, and the upper consisting of terrigenous coal-bearing sediments. Their thickness varies from hundreds of metres to 3 km. Deformation formed gentle folds and normal faults (Abdulin 1984). Further north, in the eastern part of the Middle Urals (Chelyabinsk area, Fig. 21 e), as well as in the base of the Mesozoic cover of the West Siberian basin (Fig. 21f) and in the Tagil zone (Fig. 21g), narrow, linear graben-like depressions are filled by Triassic trapp volcanics and terrigenous, partly coal-bearing, mostly alluvial sediments, up to 2–3 km thick. The margins of the depressions are affected by sharp folds and thrusts, usually several km in amplitude, often oppositely vergent (Tuzhikova 1960; Rasulov 1972).

Timan (Fig. 21 h) did not experience uplift either in the Carboniferous, or even in the Late Permian, so its structure is not Late Palaeozoic (Raznitsyn 1968). It was covered by a shallow sea during the Kazanian transgression and was a place of terrigenous sedimentation in intracontinental basins during the Tatarian (end of Permian). In Early Triassic time, block faulting led to some local erosion, but Timan was not an obstacle for the transport of polymictic sandstones from the Urals to the central parts of the East European platform. Uplift and deep erosion of the growing Timan Range took place later than the Early Triassic, but before the Mid-Jurassic. The latter lies unconformably over different horizons of Late Palaeozoic age and has basal conglomerates with clasts of metamorphic schists from local uplifts of the basement.

In the western slope of the Cis-Polar (I) and Polar Urals, the Triassic terrigenous sediments (up to 2200 m thick) are weakly coaliferous and partly variegated. They are underlain by a continuous cover of trapp volcanics in the Kosyu–Rogovskaya (Fig. 21j) and Korotaikha (Fig. 21k) depressions of the Uralian foredeep. Subhorizontal over large areas, they possess an intense thrust-and-fold character in local, narrow linear zones such as the Chernyshov (Fig. 211) and Chernov (Fig. 21m) ranges (Puchkov 1975; Timonin 1976).

Pay-Khoy (Fig. 21 n) is a Mesozoic alpine-type foldbelt. According to palaeogeographic, structural and isotopic data, it is superimposed on a deep Permian molasse basin, a former part of

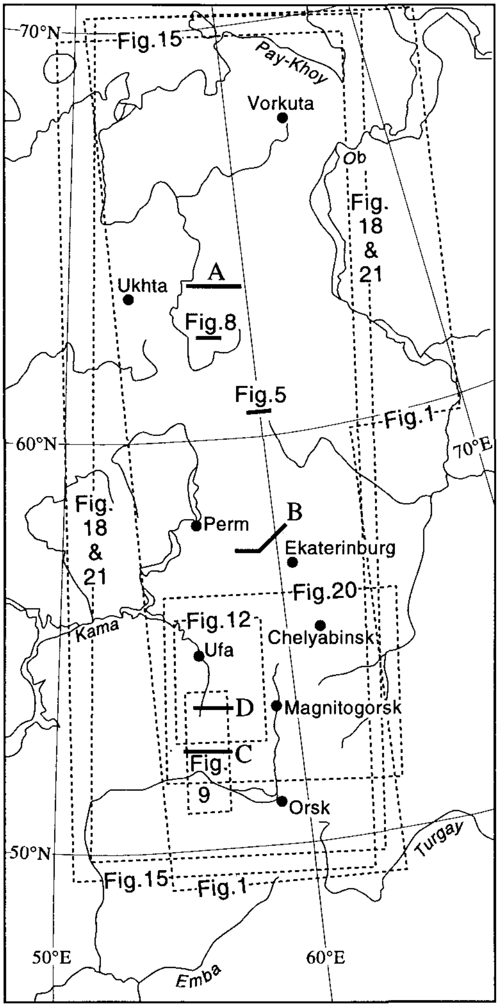

Fig. 23. Geographical location of previous figures. Sections: A, B and C are the Cis-Polar, Middle and Southern Urals sections of Fig. 4, respectively. D: section of Fig. 13.

the Uralian foredeep (Chermnykh 1972; Korago *et al.* 1989; Yudin 1994).

This tentative scheme of the Old Cimmerian deformations allows two important conclusions. First, the western boundary of the area with intense Old Cimmerian deformation has a northeastern strike and crosses at some angle the Uralian structural boundaries. Second, the 'en echelon' character of the deformations, especially the NW-trending, SW-verging structures of Timan and Pay-Khoy, suggests a sinistral, transpressional origin. On this basis, it can be also suggested that the Uralian structure of the Polar Urals continues to the north, and is substituted by a younger, pre-Mid-Jurassic foldbelt immediately to the west of it.

The southern continuation of the Urals was different at different stages in its history. As was pointed out earlier in this paper, the early orogenic uplift in Famennian–Tournaisian time, reflected in the development of the Zilair flysch, can be traced from the Urals to the south and southwest as the South Emba foldbelt (Fig. 19), connecting the Urals with the Variscides of the Greater Caucasus. But before the end of the Early Carboniferous (after the Mid-Viséan) this orogen ceased to develop, as is reflected in the presence of predominantly carbonate facies in the Late Viséan–Late Carboniferous of the southeastern margin of the Pricaspian basin (Volozh 1991). Conversely, the Mid- and Late Carboniferous orogenic movements of the Urals are reflected in the presence of coarse terrigenous facies in the northeastern part of the basin. These and the Permian movements are correlated with the analogous events in the Southern Tien-Shan, which are explained as a result of collision between the Kazakhstano–Kirgizian and Tarimo–Tadzhikian continental masses in the process of closure of Turkestanian ocean and formation of the South Tien-Shan suture zone of Pangaea (Puchkov 1991; Fig. 19).

The origin of the modern Ural mountains

The Late Palaeozoic mountain belt rejuvenated by the Old Cimmerian dislocations existed only for a short time, due to a rapid erosion. By the end of the Jurassic and during the Cretaceous the Urals were low hills and partially a lowland ingressed and covered by seas (Papulov 1974). Only since the Late Oligocene have the Ural mountains started to grow again (Rozhdestvensky 1994). These processes are still active, proved by geodetic and horizontal stress measurements as well as by earthquakes of weak to medium magnitude (Aleynikov *et al.* 1976). This orogeny probably results from an intracontinental deformation that followed favourable directions in the lithosphere of Eurasia. As indicated earlier (Puchkov 1988*b*), the Urals bisect the angle made by the southern, convergent margin of the modern Eurasian lithospheric plate (Fig. 22).

Conclusions

The general features of the Uralian orogen are summarised in a simplified diagram (Fig. 20), representing the Southern Urals, the best exposed area of the orogen. The following typical structural elements can be established from west to east.

The Uralian foredeep: filled with Permian molasse, underlain by Palaeozoic shelf deposits of the East European continent. It is divided into the following units: 1.1, the chain of the Early Permian barrier reefs at the western boundary of the foredeep; 1.2, the outer part of the foredeep, characterized by gentle, platform-type structures or (where Kungurian salt is present) by salt ridges; 1.3, salt ridges of the southern part of the foredeep; 1.4, the frontal line of the west-vergent thrusts and folds of the orogen; 1.5, the internal part of the foredeep, characterized by a thin-skinned to medium-skinned style of thrust-and-fold structure and probably by the presence of wedge-like (underthrust, backthrust) structures at the boundary with the next zone to the east; 1.6, the transverse Kara-Tau uplift, dividing the foredeep into basins.

The West Uralian zone: 2.1, mostly west-vergent thrust-and-fold structures of a thin- to thick-skinned style, affecting Palaeozoic shelf and bathyal deposits of the passive margin of the Palaeozoic East European continent; 2.2, backthrusts characteristic of the eastern limb of the Zilair synform; 2.3, the axial part of the Zilair synform; 2.4, allochthons (klippen) composed of ophiolites and bathyal complexes situated in the axial part of the synform.

The Central Uralian zone: 3.1 and 3.2 – the core of the Bashkirian anticlinorium, an exhumed Pre-cambrian basement of the Palaeozoic continental margin, including crystalline complexes, produced by two or more stages of deformation and metamorphism, sedimentary sequences of Riphean aulacogens and Vendian molasse of the Late Precambrian Pre-Uralian orogen. Structures of the western part of zone 3.1 are Variscan, their morphology being close to those of the West Uralian zone. Structures in the eastern and northern parts of zone 3.2 are a complex result of two or more deformational phases (Variscan and Pre-Variscan); 3.3 – 3.5, the Ural-Tau metamorphic complex, probably Palaeozoic; 3.3, the Yantyshevo–Yuluk backthrust; 3.4, the Maksyutovo metamorphosed accretionary complex of a Devonian island arc(?); 3.5, the Suvanyak metamorphosed bathyal complex of the passive margin of the East European continent; 3.6, the Main Uralian Fault, represented by an east-dipping zone of serpentinitic melange. Elements 3.3–3.6 are conventionally attributed to the Central Uralian zone.

The Tagilo–Magnitogorskian zone: 4.1, Internal melange zones (thrusts); 4.2, central rift of Early Carboniferous age, marked by intrusions of a mantle-derived gabbro–granitic complex and comagmatic trachyrhyolite–basalt volcanics; 4.3, backthrusts of the eastern boundary of the zone (serpentinitic melanges); 4.4, the axial part of the Magnitogorsk synform.

The East Uralian Zone: This is a collage of microcontinental blocks with relicts of an autochthonous Palaeozoic sedimentary and volcano sedimentary cover (5.1) and allochthonous Palaeozoic ophiolite and island-arc formations (5.2); 5.3, the Main Granitic Axis of the Urals; 5.4; the Denisovka suspected suture zone, with ophiolites and serpentinitic melanges; 5.5, thermal domes with Barrovian metamorphism and uplifted Early Proterozoic complexes; 5.6, relicts of intermontane depressions, filled with Middle Carboniferous (Moscowian) flysh-like deposits and probably Upper Carboniferous molasse.

The Transuralian Zone: this is a volcano-plutonic belt composed mainly of calc-alkaline magmatites. 6.1, the Urkash fault (suture zone?), a suggested boundary between the Urals and the Kazakhstanides; 6.2, a hypothetical relict of an intermontane basin.

The Kazakhstanides: 7.1, Variscan uplifts; 7.2, Variscan intermontane depressions, filled with Carboniferous and Permian molasse (to the east of the limits of the scheme).

The following are the most important stages of development of the Urals since the latest Precambrian.

(1) Vendian: continental collision and orogeny resulting in the Pre-Uralian (Timanides) foldbelt, which was probably part of the Cadomian orogenic belt within the Rodinia super-continent.
(2) Late Cambrian–Early Ordovician: rifting, break-up of the super continent, formation of the Palaeo-Uralian ocean and the passive margin of the East European continent.
(3) Mid-Ordovician–Mid-Devonian: subduction and accretion along the active margin of the Kazakhstanian continent on the eastern side of the Palaeo-Uralian ocean.
(4) 'Soft' and oblique collision between the passive and active margins, starting in the Southern Urals in the Late Frasnian and in the Northern Urals in the Late Viséan.
(5) 'Rigid' collision between the continents started in the Mid-Carboniferous. The oblique character of the collision was maintained until the Late Permian; with

time the orogenic processes gradually became more intense in the north than in the south.

(6) At the Permian–Triassic boundary: an episode of dissipated (areal) tension accompanied the development of a vast volcanic (trapp) province (including the Urals, Timan, Novaya Zemlya, Taymyr, Western and Eastern Siberia).

(7) Continental and intracontinental collision took place shortly before the Middle Jurassic. It affected the northern and eastern parts of the Urals and created the Timan Range, Chernyshov and Chernov thrust-and-fold zones and the Pay-Khoy–Novozemelian foldbelt.

(8) A long tectonic pause between the end of Jurassic and Late Palaeogene, led to the complete erosion of the Variscan Uralian orogen.

(9) Since the Late Oligocene, a new phase of intracontinental deformation led to the modern Ural mountains.

Future research in the Urals should focus on some of the targets listed below.

(1) The search for more reliable data on Precambrian ophiolites and calc-alkaline volcanics in the Urals with a geodynamic analysis of the Pre-Uralian (Timanides) foldbelt.

(2) Reliable palaeomagnetic determination of ancient pole positions of continents and terranes enclosed in the Urals. In particular Riphean, Vendian, Silurian and Devonian palaeolatitudes are needed.

(3) Creation of improved paleocontinental reconstruction, especially for the Vendian time.

(4) Research on the stratigraphy and tectonic nature of the Uralian Cambrian.

(5) Geological and isotopic age study of the areas affected by HP–LT and other types of metamorphism. The finds of Palaeozoic fauna in the Maksyutovo complex of the Southern Urals makes one anticipate analogous finds in some other metamorphic terranes which are now thought to be Precambrian.

(6) A thorough basin analysis must be applied to the Proterozoic and Palaeozoic sections of the Western slope of the Urals and adjacent area of the East European platform, as former parts of a single basin.

(7) Determination of directions of tectonic transport for many thrusts (e.g. checking the backthrust concept along the eastern limb of the Magnitogorskian synform). Very important are structural studies aimed at palinspastic reconstruction of the orogen. Also very important are structural studies of the metamorphic terranes of the Urals.

(8) Deeper study of the easternmost structures of the Urals and better definition of their boundary with the Kazakhstanides.

(9) Geological interpretation of the international geophysical profile URSEIS–95 Sterlitamak–Novonikolayevka (Southern Urals) which is close to completion while this article is being edited. There is hope that the profile will provide more detailed and reliable knowledge of the deep structure of the Urals. Combined with the other seismic profiles and applied to geological data, it gives a basis for creation of a 4D model of the Urals.

(10) Use of structural and geodynamic data to better understand the metallogeny of the Urals.

(11) Transformation of geological data of the Urals into digital form, using geoinformation systems (GIS).

This work was completed under the sponsorship of the Russian Foundation for Fundamental Investigations (Ref.no: RFFI 93–05–14033) and INTAS (Ref.no: INTAS–94–1857). The author expresses his deep gratitude to J.-P. Burg, M. Ford, J. Knapp and anonymous reviewers for corrections and useful suggestions they have made while evaluating and editing the manuscript. Author's e-mail address: puchkov@giras.baskiria.su.

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