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The structure of the south Urals foreland fold and thrust belt at the transition to the Precaspian Basin

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Abstract: The structural architecture of the south Urals foreland fold and thrust belt at the transition into the Precaspian Basin is that of a wedge-shaped, west-vergent thrust stack with a significant amount of basement involvement. The surface geology of this part of the thrust belt is dominated by the south Urals accretionary complex, whose internal structure was primarily developed during Late Devonian to Early Carboniferous arc–continent collision and which was subsequently incorporated into the thrust belt. A number of thrusts, identified in the field and in seismic profiles, breach the accretionary complex, suggesting that they post-date its emplacement and may be related to the development of the foreland fold and thrust belt. A basal detachment can be confidently defined only beneath the frontal part of the thrust belt, making it difficult to construct balanced and restored cross-sections and therefore to calculate the amount of shortening. Nevertheless, the amount of shortening appears to be of the order of only a few tens of kilometres. There is a major change in the structural style along the frontal part of the thrust belt that may be related to basement topography and/or basement response to the deformation across a basement fault oriented at a high angle to the structural grain of the thrust belt.

Keywords: Urals, Precaspian Basin, structural geology, fold and thrust belts, forelands.

The structural architecture of the south Uralide foreland fold and thrust belt has often been compared with that of other thrust belts from around the world, especially that of the Appalachians (e.g. Kamaletdinov 1974; Kruse & McNutt 1988; Rodgers 1990; Knapp *et al.* 1998). Although there are similarities, recent structural mapping and reflection seismic data have shown the structural architecture of the south Uralide foreland fold and thrust belt to be different in a number of aspects, in particular in the following features: (1) the amount of basement involved; (2) the influence of pre-existing basement structures in focusing deformation and causing along-strike structural changes; (3) the small amount of shortening; (4) the location of a possible basal detachment within the basement (Brown *et al.* 1997, 1998, 1999; Perez-Estaun *et al.* 1997; Giese *et al.* 1999; Alvarez-Marron *et al.* 2000; Alvarez-Marron 2002). The majority of recently published studies of the Uralide fold and thrust belt have dealt with the structure of Precambrian rocks of the Bashkirian Anticlinorium and the Palaeozoic platform and foreland basin sediments along its western and southern flank (Fig. 1). The part of the fold and thrust belt extending from the southern termination of the Bashkirian Anticline (*c.* 53°N) southward to the Precaspian Basin has not been extensively studied, although schematic cross-sections by Kamaletdinov (1974) and Zholtayev (1990), and a partial section by Bastida *et al.* (1997) and Perez-Estaun *et al.* (1997), suggest a different structural style from that of the area in and around the Bashkirian Anticline. The south Uralide fold and thrust belt also extends southward for several hundred kilometres beneath and along the margin of the eastern Precaspian Basin. Uralide structures in this area have been interpreted from borehole and seismic data to be a west-vergent thrust stack that is thought to exert important control on the localization of petroleum in this part of the basin (Zholtayev 1990; Nevolin & Fedorov 1995; Brunet *et al.* 1999; Barde *et al.* 2002; Volozh *et al.* 2003). Determining the structural architecture of the southernmost part of the fold and thrust belt is therefore important for understanding the basement structure (Uralide) of the southeastern Precaspian Basin, particularly in the Aktyubinsk region of Kazakhstan.

Geological background

The southwestern part of the Uralide orogen (Fig. 1) developed in two stages during the Mid- to Late Palaeozoic. In the Mid- to Late Devonian the continental margin of Baltica was subducted eastward beneath the Magnitogorsk volcanic arc and an accretionary complex was developed and emplaced over the subducting slab as the arc collided with the continental margin (Puchkov 1997; Brown *et al.* 1998; Brown & Spadea 1999). From the Late Carboniferous to the Late Permian–Early Triassic, the palaeo-Uralian ocean basin to the east of the Magnitogorsk arc closed as the Siberian plate collided with Baltica (which by then also included the accreted volcanic arc). The closure of the palaeo-Uralian ocean basin was contemporaneous with westward thrusting of the East European Craton Precambrian basement (i.e. part of the cratonic nucleus of Baltica involved in the Uralide orogen) and its Palaeozoic platform cover, to form a foreland fold and thrust belt and foreland basin (Kamaletdinov 1974; Brown *et al.* 1997; Puchkov 1997).

In this paper we define the south Uralide foreland fold and thrust belt to be that part of the orogen that developed during the latest Carboniferous to Early Triassic and that involved the continental margin of Baltica. In this definition the south Urals accretionary complex was affected by the foreland fold and thrust belt deformation, although much of its internal structure (see below) is related to the Mid–Late Devonian to Early Carboniferous arc–continent collision. The foreland fold and thrust belt extends from the main arc–continent suture (the Main Uralian fault) westward to the deformation front. North of *c.* 53°N, the foreland fold and thrust belt is a *c.* 150 km wide, west-

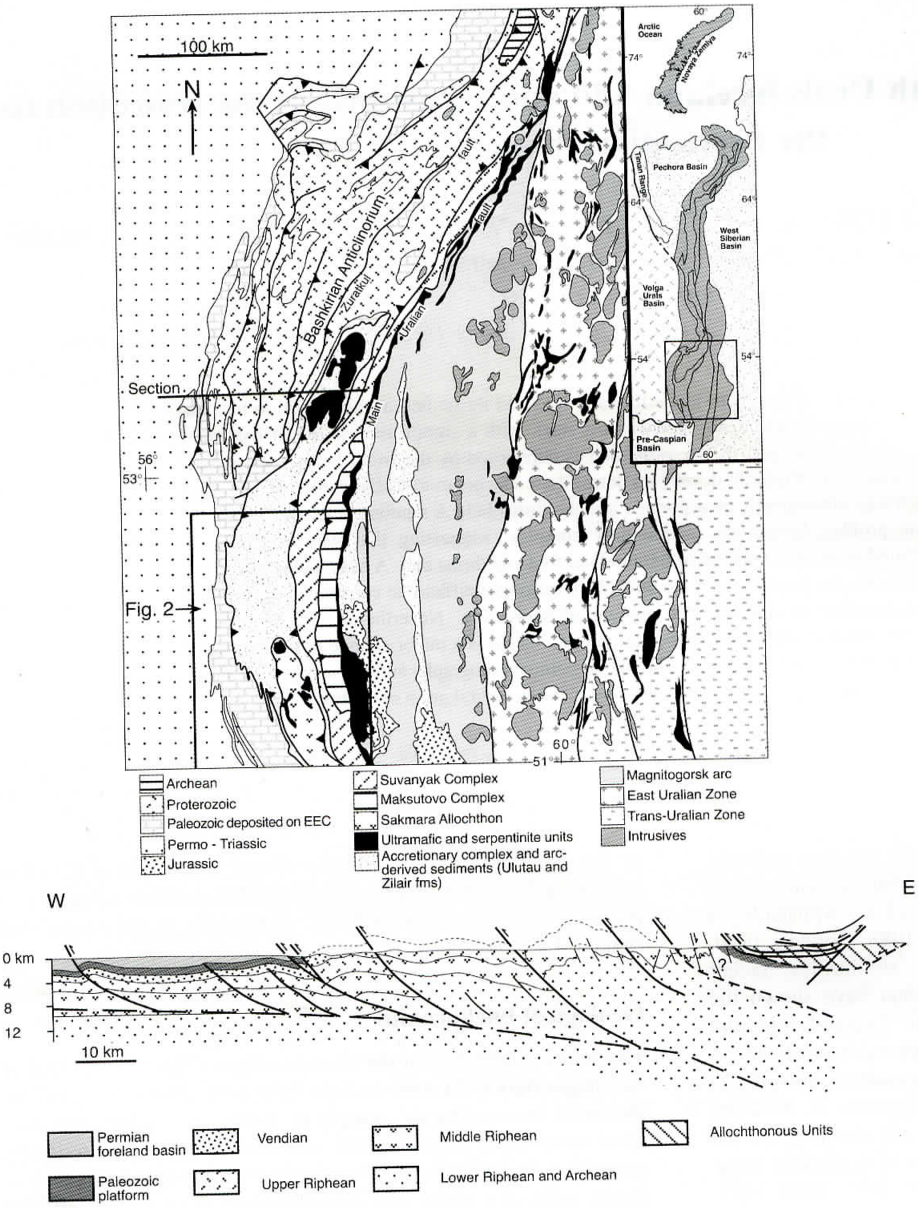

Fig. 1. Geological map and cross-section of the south Urals. The cross-section is from Perez-Estaun *et al.* (1997). The location is shown in the inset. The location of Figure 2 is also shown. EEC, East European Craton.

vergent thrust stack made up of Precambrian basement, the Late Devonian accretionary complex, Palaeozoic platform deposits, and foreland basin sediments (Fig. 1). Palaeozoic shortening in this part of the thrust belt is small in comparison with other mountain belts, *c.* 20 km or less (e.g. Brown *et al.* 1996, 1997, 1999; Perez-Estaun *et al.* 1997; Giese *et al.* 1999). It also exhibits a high degree of along-strike structural variation and basement involvement, which has been interpreted to have been caused by pre-existing structures in the basement (Perez-Estaun *et al.* 1997; Brown *et al.* 1999). South of 53°N the south Uralide foreland is dominated by the accretionary complex (Brown *et al.* 1998; Alvarez-Marron *et al.* 2000) (Fig. 1), with only a narrow band of folds forming the outcropping frontal structure of the fold and thrust belt.

Lithotectonic units

The accretionary complex

The Sakmara allochthon (Figs 1 and 2) structurally overlies the Zilair Nappe in the south and forms the uppermost unit of the accretionary complex in the study area. It is composed of a number of imbricate thrust units involving Ordovician to Devonian sediments, volcanic rocks and ophiolites (Kamaletdinov 1974; Puchkov 2002). Discussion of the Sakmara allochthon is beyond the scope of this paper.

The Zilair Nappe (Figs 1 and 2) consists of *c.* 4000–5000 m (structural thickness) of westward-younging, Frasnian to Early Tournasian age (Late Devonian–Early Carboniferous) polymictic turbidites of the Zilair Fm. The provenance of the Zilair Fm sediments is from both the accretionary complex and the Magnitogorsk arc (Gorozhanina & Puchkov 2001; Willner *et al.* 2002) and the depositional environment was that of a peripheral foreland basin developed in front of an arc–continent collision. The metamorphic grade in the Zilair Nappe increases eastward from anchizone to lowermost greenschist facies (chlorite zone) (Bastida *et al.* 1997). A sequence of Ordovician, Silurian and Early and Mid-Devonian sediments may underlie the Zilair Fm and even be incorporated into the Zilair Nappe, but its presence and its thickness are not known for certain.

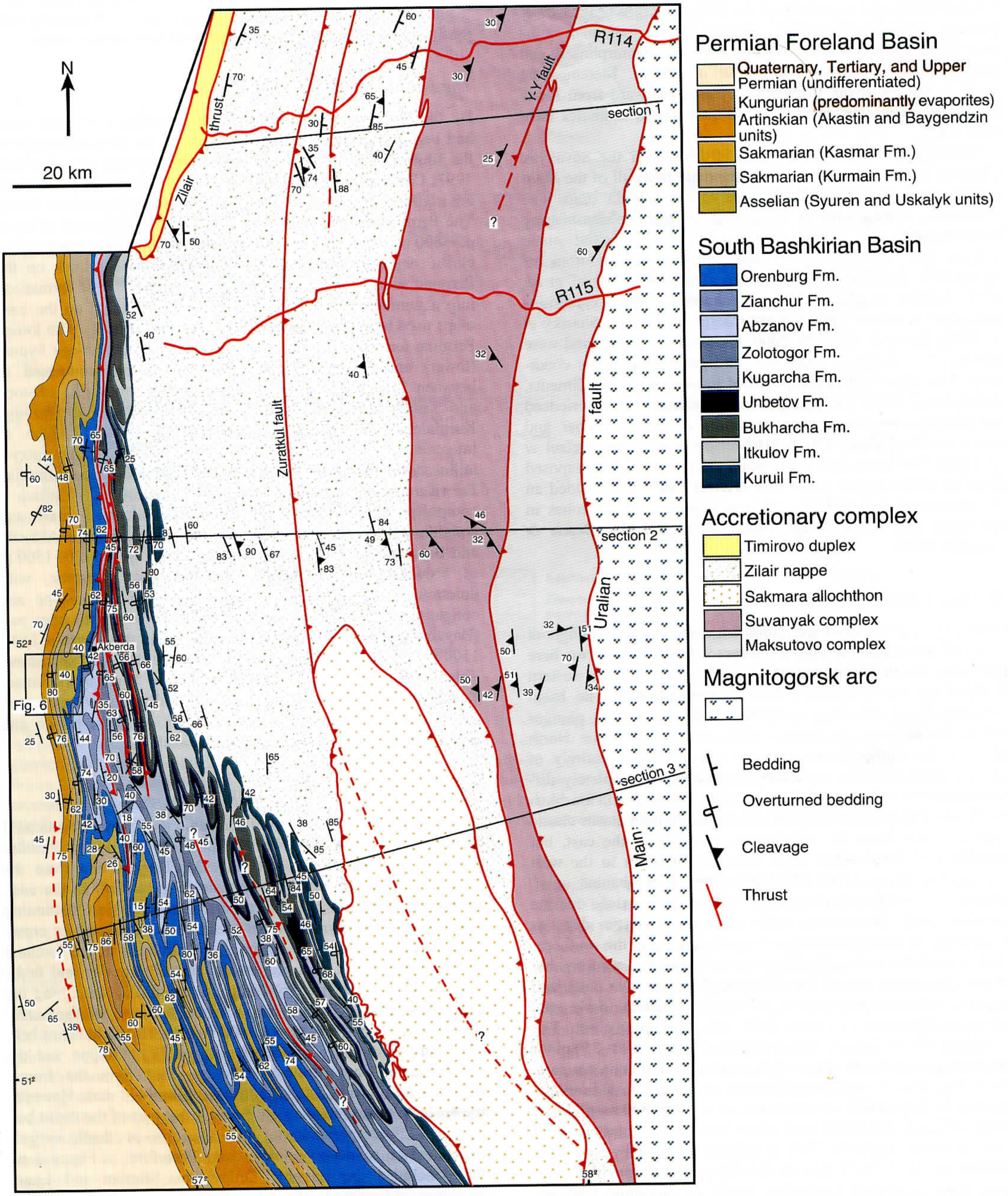

Fig. 2. Geological map of study area based on the Geology of the USSR 1:200 000 South Urals Map Series with our own data and observations (except for dip data in the Maksutovo Complex, which are from Hetzel *et al.* (1998)). The locations of the three cross-sections (Fig. 3), seismic profiles R114 and R115, and Figure 6 are shown.

To the east of, and structurally below the Zilair Nappe, the Suvanyak Complex (Figs 1 and 2) is composed of moderately to strongly deformed phyllite and quartzite thought to represent the Palaeozoic bathyal sediments of the Baltica margin (Zakharov & Puchkov 1994; Puchkov 2002). During the arc–continent collision these sediments were polydeformed, metamorphosed and thrust westward (Alvarez-Marron *et al.* 2000). Metamorphic grade in the Suvanyak Complex increases eastward from lower to middle greenschist facies, but no quantitative estimates have been made.

The Maksutovo Complex, which is thrust over the Suvanyak Complex in the east and is in the immediate footwall of the Main Uralian fault (Figs 1 and 2), consists of two tectonic units. The structurally lowest unit is composed of glaucophane-bearing metasediments and minor amounts of blueschist and mafic eclogite that record pressure and temperature conditions of 20 ± 4 kbar and 550 ± 50 °C (Beane *et al.* 1995; Hetzel *et al.* 1998; Schulte & Blümel 1999). Peak metamorphic conditions took place at around 380–370 Ma (Matte *et al.* 1993; Shatsky *et al.* 1996; Beane & Connelly 2000; Glodny *et al.* 2002) and were followed by retrograde blueschist- and greenschist-facies conditions. The upper unit is composed of Palaeozoic metasediments, metavolcanic rocks and a serpentinite mélange that experienced metamorphic conditions with pressures of around 8 kbar and temperatures of about 450 °C (Dobretsov *et al.* 1996; Hetzel *et al.* 1998). The lower and upper units are tectonically juxtaposed along an ENE-vergent shear zone (Hetzel 1999) that yielded an Ar–Ar age of 365–355 Ma, whereas retrograde shear zones in the upper unit range in age from 339 to 332 Ma (Beane & Connelly 2000).

The South Bashkirian Basin

During the late stages of arc–continent collision, and throughout much of the Carboniferous, a successor basin (which we here name the South Bashkirian Basin) formed along the western flank of the arc–continent collision mountain belt. The basin currently crops out from *c.* 53°N southward to (and plunges below) the Mesozoic sediments of the Precaspian Basin. North of 53°N the Carboniferous deposits consist almost entirely of shallow-water platform carbonates, indicating a completely different depositional environment from that of the South Bashkirian Basin. The provenance of the South Bashkirian Basin clastic sediments was from the accretionary complex to the east, but possibly with local minor input from the platform to the west and north (Mizens 1997; Chuvashov 1998; Gorozhanina *et al.* 2001). The basin contains some 4000 m of mainly marine turbidites and limestones, with continental clastic deposits dominating in the Upper Carboniferous sequence in the southernmost part of the basin. The Tournaisian Kuruil Fm conformably overlies the upper unit of the Zilair Fm (the Mazitovo unit), and is composed of up to 300 m of cherty siltstone, dark grey siliceous limestone, siliceous shale and dark grey chert. The overlying Viséan Itkulov Fm is composed of *c.* 500–550 m of limestone, siltstone, siliceous shale, sandstone and conglomerate. Overlying this is the Serpukhovian to early Bashkirian-age Bukharcha Fm, which is composed of *c.* 250–340 m of limestone, siliceous limestone with chert lenses, and limestone with local siltstone interbeds. This is in turn overlain by *c.* 1700–2900 m of early Bashkirian to Gzelian-age siltstone (the main rock type), limestone (including levels of limestone breccia), calcareous sandstone and/or sandy limestone, with local beds of marl and conglomerate (Fig. 2). On the basis of faunal ages this succession has been divided into a number of formations (svita) by Russian stratigraphers (Khvorova 1961) (Fig. 2), but because of the overall uniformity of the succession in the field, and for simplicity of the description here, we have grouped these together. They are shown separately in Figure 2, in keeping with the Russian 1:200 000 maps that are used here as base maps.

The Uralide foreland basin

By the latest Carboniferous to Early Permian a foreland basin had begun to develop along the whole of the western margin of the southern part of the evolving Uralide orogen (e.g. Puchkov 1997; Chuvashov 1998; Proust *et al.* 1998). Deposited sediments are conformable on top of those of the South Bashkirian Basin. The Permian sediments in the study area are composed of up to *c.* 5800 m of deep to shallow marine- and continental-facies clastic deposits, limestone and evaporite. Recent work on the Permian sequences has resulted in the subdivision of formations into a number of different units from those shown on the base maps used here (e.g. Chuvashov *et al.* 1993) (Fig. 2). The lowest Permian formations in the study area are the Asselian-age Syuren (lower) and Uskalyk (upper) Fms, which are composed of between 750 and 1000 m of conglomerate, sandstone, siltstone and sandy limestone. This is overlain by the Asselian-age Kurmainian Fm, which is composed of *c.* 200–1500 m of intercalated limestone, grey siltstone, sandstone and microcrystalline dolomite. Overlying this is the Sakmarian-age Kasmarian Fm (Karamurun, Sarabil, Maloik and Kondurov units), which is composed of *c.* 1000 m of sandstone, siltstone, marl and conglomerate. This is overlain by the Artinskian-age Aktastin and Baygendzhin Fms, which together make up *c.* 1200–1500 m of brownish grey siltstone, sandstone and limestone, with dolomite in the lower part (Aktastin Fm) and sandstone and conglomerate with limestone and chert pebbles in the upper part (Baygendgin Fm). Cropping out locally in the study area is 250–1500 m of Kungurian-age gypsum, dolomite, clay and sandstone. This is overlain by 350–700 m of Upper Permian (Ufimian, Kazanian and Tatarian stages) redbed sediments consisting of intercalations of reddish marl, sandstone, siltstone, brown and grey limestone, and polymictic conglomerate.

Foreland fold and thrust belt

Three cross-sections show the interpreted upper-crustal structural architecture of the southwestern part of the south Uralides foreland fold and thrust belt (Fig. 3). They extend from the frontal folds in the west to the Main Uralian fault in the east. Below we focus on these three cross-sections, first discussing how the depth to crystalline basement was determined for cross-section construction, next outlining the structure of the foreland fold and thrust belt, focusing on the frontal structure and faults that breach the accretionary complex, and finally describing the Late Devonian to Early Carboniferous structure of the accretionary complex, which predates the foreland fold and thrust belt. The surface structure, especially in the Zilair Nappe and the Carboniferous and Permian sediments that form the frontal structure in the west, is well constrained by field data. However, the absence of an oblique view through this part of the thrust belt makes the interpretation of the structure at depth entirely dependent on reflection seismic data. Therefore, in Figure 3 we have included the possible Ordovician, Silurian and Lower Devonian sediments in the Zilair Nappe. Two reflection seismic profiles (R114 and R115) (see Fig. 5) across the accretionary complex were acquired by Bashneftegeofizika in the 1980s and have been reprocessed from the original field tapes at Uppsala

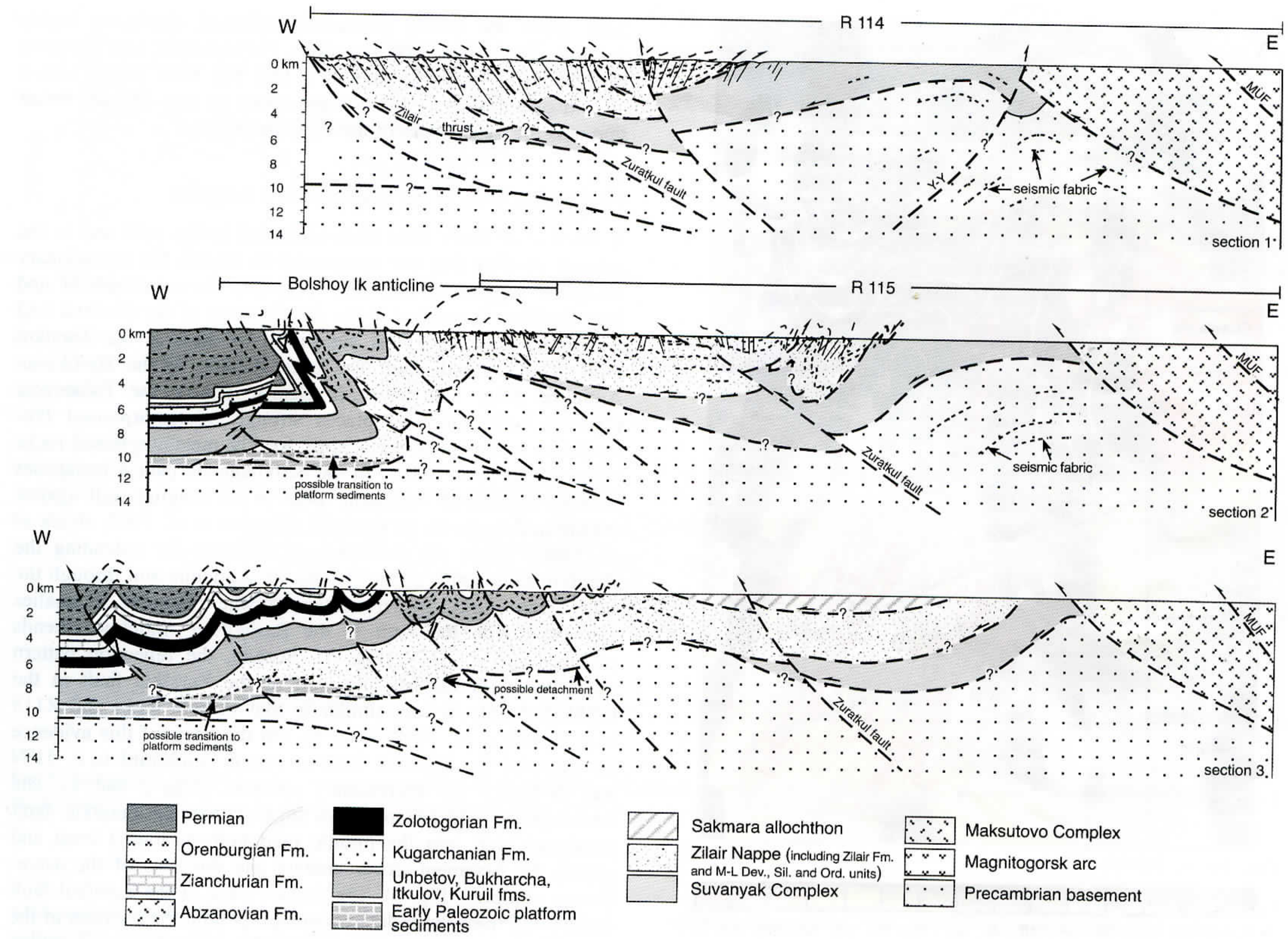

Fig. 3. Schematic cross-sections through the foreland fold and thrust belt. For simplicity in the display all units in the Permian have been grouped into one pattern, as have the Lower Carboniferous Unbetov, Bukharcha, Itkulovo and Kuruil formations. The Zilair Nappe as shown includes Ordovician, Silurian, and Lower to Middle Devonian units that are interpreted (e.g. Senchenko *et al.* 1977) to overlie the basement, as well as the Zilair Fm. It is not known for certain how far westward the deformation associated with the Zilair Nappe, or the Zilair Fm itself, extends. The parts of sections 1 and 2 covered by R114 and R115, respectively, are shown. The Akberda borehole (black dot in Fig. 2), some 15 km south of section 2, intersects Lower and Middle Devonian limestones at 3000 m depth (Schekotova 1987). The geometric constraints placed on the section construction by the surface data do not allow us to include these data in the cross-section. MUF, Main Uralian fault.

University. The two profiles were described in detail by Brown *et al.* (1998) and only the key data and features relevant to this paper are presented and summarized here.

Depth to basement

The depth to the Archaean crystalline rocks has been estimated for much of the central and south Urals on the basis of reflection seismic profiling, gravity data and, where possible, borehole data (see Peterson & Clarke 1983; Svetlakova 1993; Puchkov 2002). The top of the Archaean crystalline basement determined in this way for the frontal structure correlates well with magnetic highs and lows in the total field aeromagnetic pattern (Fig. 4) (see also Brown *et al.* 1999), thereby allowing the topography of this surface to be indicated with some confidence relative to this dataset. Proterozoic (Riphean and Vendian) sediments may locally overlie the Archaean rocks in the study area, but their presence and thickness are not known for certain. The depth to the top of the basement in the frontal part of the thrust belt is interpreted to deepen from *c.* 7 km in the Orenburg Arch to more than 9 km towards the NE to north, and to greater than 11 km towards the SE to south (Svetlakova 1993) (Fig. 4). In the cross-sections we have determined a depth to a possible detachment of roughly 10 km below the frontal structure on the basis of known sediment thicknesses and geometric constraints during section construction (see also Fig. 4). Eastward, beneath the accretionary complex, the Archaean basement is only very weakly magnetized (Ayala *et al.* 2000), but profiles R114 and R115 image the Precambrian basement as thick bands of continuous, openly concave-downward reflections in the east that suggest that the basement forms an open anticline, shallowing to *c.* 2–3 km depth (PB in Fig. 5).

Frontal structure

Between *c.* 53°N and *c.* 51°40′N (Fig. 3, section 2) the frontal structure is characterized by a 10–15 km wide band of kilometre-scale, north–south-trending, shallowly north-plunging,

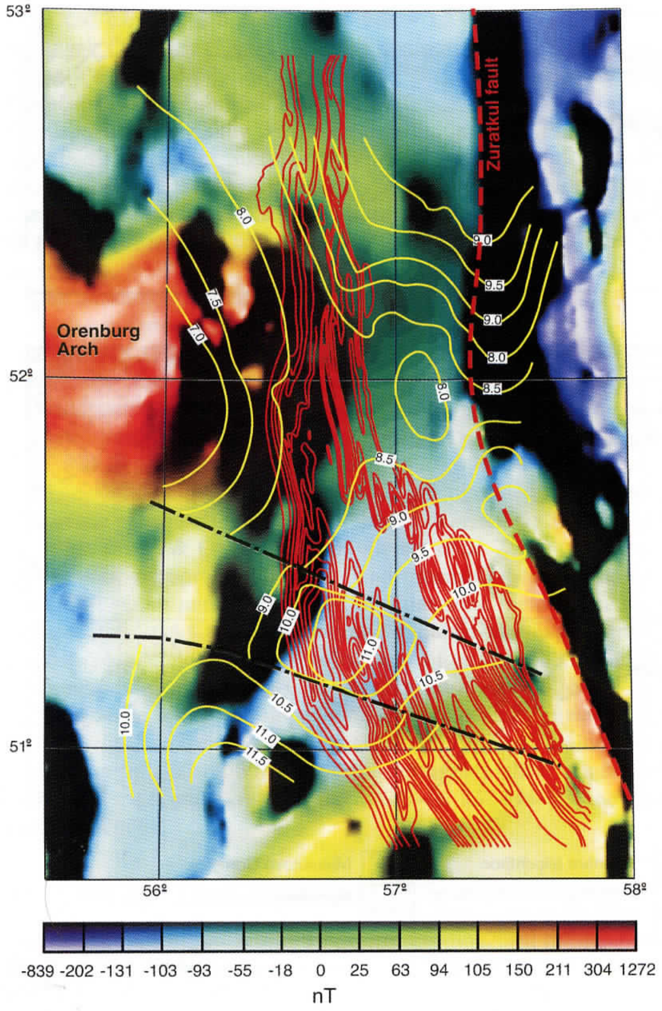

Fig. 4. Aeromagnetic map of the study area showing the depth to basement (in yellow) and the formation boundaries of the frontal structure (in red) as illustrated in Figure 2. An interpreted SE-striking basement fault is indicated by the black dashed lines. It should be noted that there is a sharp change from strongly magnetic basement to weakly magnetic basement, indicating the position of the Zuratkul fault.

west-vergent, often overturned folds with moderately east-dipping axial surfaces and west-verging thrusts developed on the overturned limb of the Bolshoy Ik anticline (Figs 2 and 3). Locally, the small-scale folds have a weak, spaced axial-plane cleavage. South of 51°40′N the frontal structure widens to *c.* 45 km and fold axes bend into a NW–SE orientation and are overall shallowly NW-plunging, with near-vertical axial planes and locally with a slight west or east vergence (Fig. 3, section 3). In several instances, minor thrusting has been identified in the cores of folds. The larger-scale overturned limb present in the Bolshoy Ik anticline is not developed in this area and it is difficult to correlate folds across the transition from one structural style to the other. Both areas, but especially that to the north of *c.* 51°40′N, have been slightly modified by late east-vergent thrusts and north–south-trending (to slightly non-cylindrical), open to locally overturned F_2 folds with steeply east-dipping to vertical axial planes (Fig. 6). In general, the steep to overturned limbs of the first phase small-scale folds are largely unaffected by F_2, although they may be steepened. However, the back limbs are locally extensively affected, displaying highly variable dip amounts and directions. For example, near the town of Abzanovo the back limb of a fold has been folded into a system of antiforms and synforms above an east-directed thrust that cuts the axial traces of the F_1 folds (Fig. 6).

Faults that breach the accretionary complex

A number of faults have been identified in the field and in the seismic profiles that are interpreted to breach the accretionary complex, suggesting that they post-date its emplacement and may therefore be related to the development of the foreland fold and thrust belt. The most significant of these is the Zuratkul fault. The Zuratkul fault has been defined in the Bashkirian Anticline (Fig. 1), where it clearly affects the Palaeozoic platform sediments and places strongly metamorphosed Precambrian basement rocks against weakly metamorphosed rocks (Glasmacher *et al.* 2001). In the aeromagnetic data it juxtaposes weakly magnetized basement rocks in its hanging wall against magnetized rocks in its footwall (Shapiro *et al.* 1997; Ayala *et al.* 2000). There are two lines of evidence for extending the Zuratkul fault south of the Bashkirian Anticline and through the study area. First, the truncation of the magnetic anomalies associated with the fault in the Bashkirian Anticline extends southward to *c.* 51°N (Fig. 4). Second, the reflection pattern associated with the hanging wall of the Zuratkul fault in the URSEIS profile is very similar to that in both R114 and R115 (e.g. Brown *et al.* 1998) (Fig. 5). On the basis of this evidence we interpret the Zuratkul fault to extend southward to *c.* 51°N and to breach the accretionary complex (Figs 2 and 4). The aeromagnetic and seismic data suggest that the Zuratkul fault penetrates well into the middle (and perhaps lower) crust and offsets the basement–cover contact and the base of the accretionary complex (Fig. 3). The surface trace of the Zuratkul fault determined from these datasets coincides with the location of the west-vergent Sosnovka thrust in the accretionary complex (Kamaletdinov 1974; Bastida *et al.* 1997).

In R115, two zones of moderately east-dipping reflectivity beneath the western part of the Zilair Nappe are interpreted to represent thrusts that breach the accretionary complex (Fig. 5). These thrusts appear to affect the basement at least to the base of the seismic section and they probably extend deeper, into the middle crust. These breaching thrusts may reactivate previously existing high-angle faults in the basement (the preferred interpretation) or they may branch off a basal detachment located in the middle crust.

The Yantyshevo–Yuluk fault crops out as an east-directed thrust that locally places the Suvanyak Complex on top of the Maksutovo Complex (Zakharov & Puchkov 1994). In R114, folding and truncation of reflections along the eastern margin of the Suvanyak Complex and within the Precambrian basement projects to the surface at the location of the Yantyshevo–Yuluk fault (Y–Y in Fig. 5), but cannot be identified in R115.

The accretionary complex

To the north of the study area, the basal detachment of the Zilair Nappe crops out as an east-dipping calc-mylonite with abundant kinematic indicators suggesting a westward transport direction (Brown *et al.* 1997; Alvarez-Marron *et al.* 2000). The internal structure of the Zilair Nappe is dominated by west-vergent, gently north- and south-plunging folds with a well-developed axial-plane cleavage. Along the eastern margin of the nappe folds verge to the east and the cleavage fans until it dips

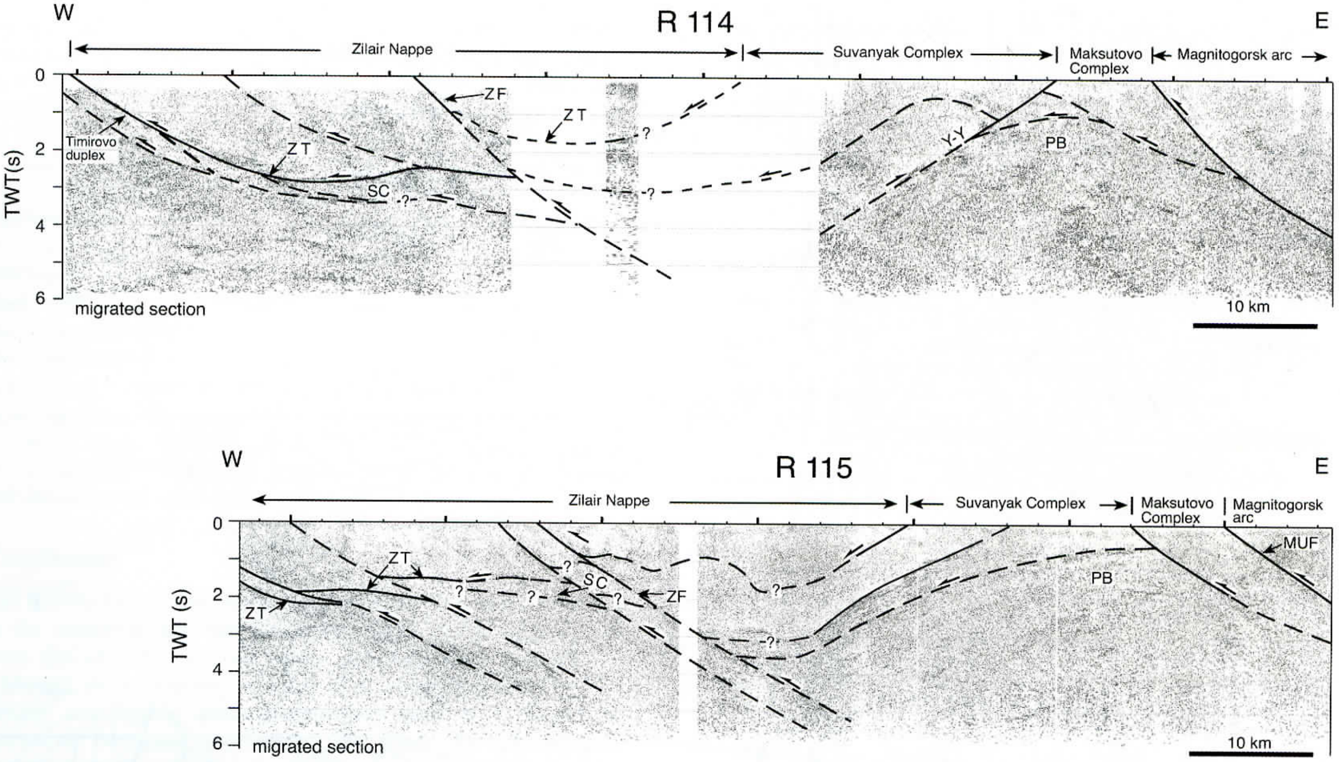

Fig. 5. Interpreted, migrated, reflection seismic profiles R114 and R115. ZT, Zilair thrust; ZF, Zuratkul fault; SC, Suvanyak Complex; Y–Y, Yantyshevo–Yuluk fault; PB, Precambrian basement; MUF, Main Uralian fault; TWT, two-way travel time. After Brown *et al.* (1998).

westward. A small number of minor thrusts have been identified within the nappe, and moderately east-dipping, discontinuous reflections in both R114 and R115 may be imaging thrusts (Alvarez-Marron *et al.* 2000). The western boundary of the Zilair Nappe in section 1, the Zilair thrust (ZT), is well imaged on profile R114 as a thin band of reflections that dips moderately eastward, where it flattens into an openly concave-downward band of reflections (Fig. 5). In R115, however, the base of the Zilair Nappe is imaged as bands of stepped, diffuse subhorizontal reflections that we interpret to indicate that the Zilair thrust is imbricated in several places. Southward, the Zilair thrust is not exposed. Because the Zilair Fm was deposited in a foreland basin we interpret it to wedge out westward in the cross-sections. This also satisfies the geometric constraints of the depth to basement and the thickness of the Carboniferous and Permian sedimentary package.

The regional-scale structure of the Suvanyak Complex is that of an upright antiform (the Uraltau antiform) that folds an earlier, locally penetrative foliation (Hetzel *et al.* 1998; Alvarez-Marron *et al.* 2000). In R114 and R115, the Suvanyak Complex is imaged as diffuse reflectivity with thin bands of curved, east- and west-dipping reflections that extend beneath the Zilair Nappe (Fig. 5). It is not clear how far westward the Suvanyak Complex extends, but on the basis of R114 and R115 we interpret it to extend to near the middle of the Zilair Nappe (Fig. 3).

The structure of the Maksutovo Complex is not well known, although Hetzel *et al.* (1998) showed it to be complexly folded locally. In seismic profiles R114 and R115 (Fig. 5) it is imaged as moderately east-dipping reflections against which the Suvanyak Complex and Precambrian basement reflectivity is truncated, suggesting that the Maksutovo Complex was thrust westward over these units. In both profiles, the Main Uralian fault (MUF in Fig. 5) coincides with the change in reflective pattern between the Maksutovo Complex and the Magnitogorsk volcanic arc to the east.

The authors have not mapped extensively inside the Sakamara allochthon and its internal structure is not discussed in this paper.

Discussion

The structural architecture of the foreland fold and thrust belt in the southernmost Urals is overall that of a west-verging, basement-cored imbricate thrust system. However, the thrust stack in this area does not have the geometry common to most foreland fold and thrust belts (Rodgers 1990) and that has been determined for the thrust belt farther north, in the Bashkirian Anticline (e.g. Brown *et al.* 1997; Perez-Estaun *et al.* 1997). Although geometric considerations during cross-section construction require a detachment beneath the frontal structure, the non-layer-cake lithostratigraphy in the area of the accretionary complex does not allow us to clearly define a detachment hinterlandward of the western flank of the thrust belt. Instead, reflection seismic data suggest that thrusts cut steeply up from the basement. It is possible that these thrusts are somehow linked in the basement, perhaps to a pre-existing detachment, giving the thrust system an overall wedge-shaped geometry. The non-layer-cake lithostratigraphy and the inability to define a detachment beneath much of the thrust belt in the study area means that it is not possible to restore the section and quantitatively determine

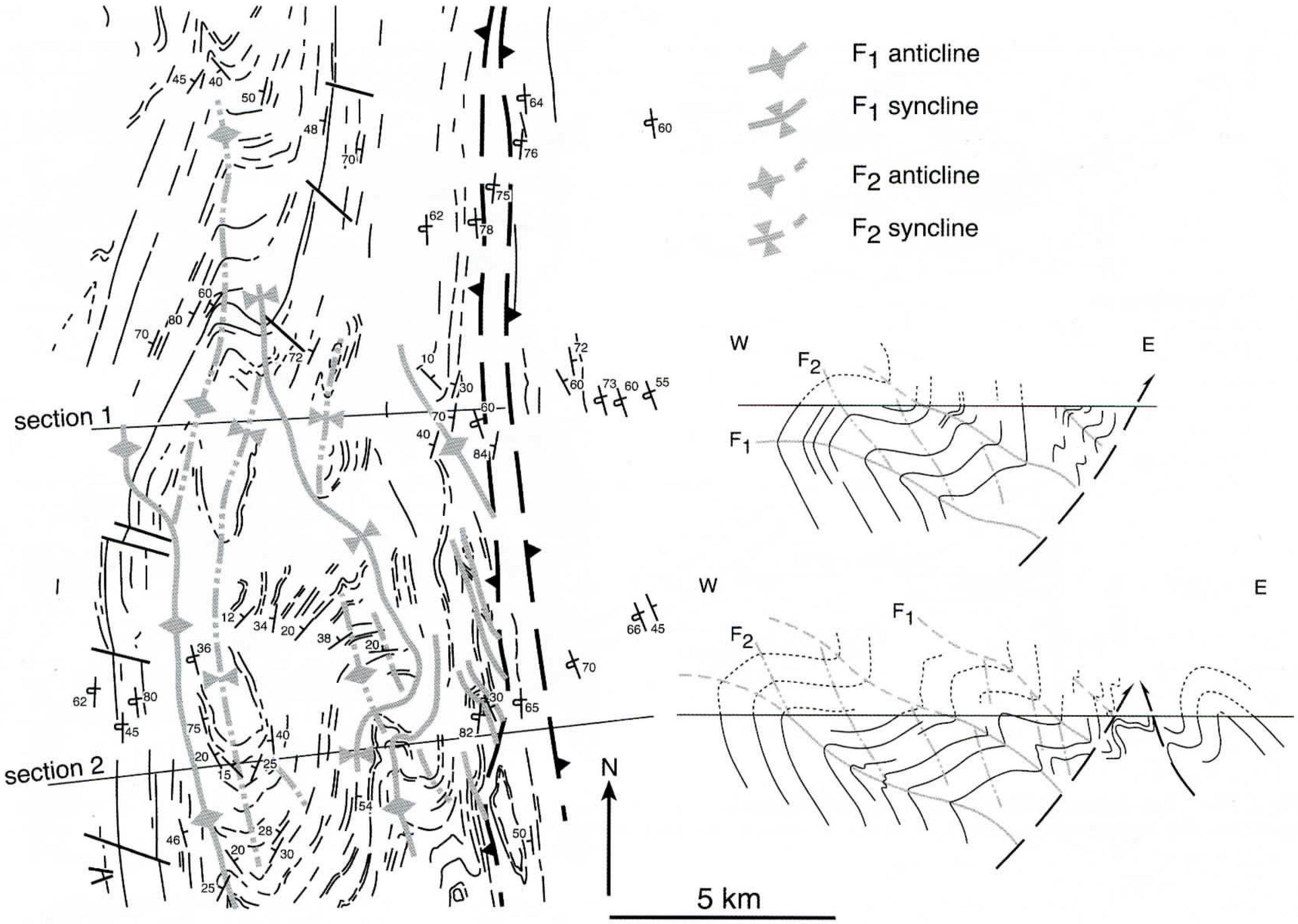

Fig. 6. Bedding form surface trace map and two schematic cross-sections showing F_2 folds overprinting the Bolshoy Ik anticline. The location is given in Figure 2.

the amount of shortening. Nevertheless, as in the Bashkirian Anticline, shortening in the study area appears to be of the order of only a few tens of kilometres, with vertical displacement along individual thrusts equalling or exceeding horizontal displacement.

There is a major change in the structural style in the frontal structure from north (section 2) to south (section 3). In the Bolshoy Ik anticline, the geometry is that of a fault propagation fold above a thrust that ramps up from the basement, accounting for most of the shortening and uplift in this area. Southward, however, the frontal structure consists of a series of (thrust-cored?) folds above a large west-dipping flank of an open basement antiform that distributes the shortening and uplift over a larger area than in the Bolshoy Ik anticline. In this area the geometry is reminiscent of a set of detachment folds, although we have not been able to identify a detachment level in the field. We suggest that the change in structural style may be related to two basement features: (1) differing basement configuratons and/or basement response to the deformation across a basement fault oriented at a high angle to the structural grain of the thrust belt (Fig. 4), similar to the cause of along-strike variations that occur in the thrust belt farther north, in the Bashkirian Anticline (e.g. Perez-Estaun *et al.* 1997; Brown *et al.* 1999); or (2) the localized buttressing around the Orenburg Arch basement high (Fig. 4).

In the study area, the surface geology of the foreland fold and thrust belt is dominated by the south Urals accretionary complex. The internal structure of the accretionary complex was primarily developed during the Late Devonian to Early Carboniferous when it was emplaced over the continental margin of Baltica during arc–continent collision. Distinguishing the accretionary complex structures from those of the foreland fold and thrust belt is not always possible in the field. However, accretionary complex folds and thrusts developed in the Zilair Nappe, for example, are recognizable by the pervasive and intense cleavage development associated with them (Alvarez-Marron *et al.* 2000), something that is not developed in the frontal structure. Thrusts that can be recognized from the seismic profiles as breaching the Zilair Nappe are generally associated with localized steepening (even overturning) and folding of the cleavage at the surface. We interpret these thrusts as being related to the development of the foreland fold and thrust belt. Farther east, in the Suvanyak and Maksutovo complexes, poor exposure makes it very difficult to differentiate the relative timing of structures.

The basement that underlies the northeastern Precaspian Basin includes part of the south Urals foreland fold and thrust belt, and the related structures are thought to provide important control on the location of oil deposits in the area. In a number of recent publications (e.g. Zholtayev 1990; Barde *et al.* 2002; Volozh *et* *al.* 2003) simplified cross-sections show the south Urals thrust belt beneath this part of the Precaspian Basin to be a west-vergent thrust stack with a significant amount of shortening and imbrication. These cross-section interpretations are largely based on borehole and reflection seismic data, as exposure of the Uralides in the area is poor or nonexistent. The structure of the south Urals foreland fold and thrust belt determined in this and previous studies (e.g. Brown *et al.* 1997, 1999; Perez-Estaun *et al.* 1997) suggests that its structural architecture beneath the Precaspian Basin might well be that of a west-vergent thrust stack with significant Precambrian basement involvement, but that it most probably narrow and has relatively little shortening and imbrication. It also suggests that care must be taken in interpreting a 'universal' structural architecture, as abrupt along-strike structural changes are common along the exposed Middle to South Uralide foreland fold and thrust belt. The only common factors are that the foreland fold and thrust belt is very narrow and displays very little shortening.

Conclusions

The architecture of the south Urals foreland fold and thrust belt at the transition into the Precaspian Basin varies significantly from that of a thin-skinned wedge detached above a basement. Although its architecture is that of a wedge (possibly with a steeply east-dipping basal detachment) there is a significant amount of basement involvement. The reason for the extensive basement involvement is interpreted to be the result of reactivation of pre-existing faults, such as the Zuratkul fault, as thrusts. Reactivation of these faults meant that a basal detachment did not develop at the basement–cover interface. Although it is possible that the thrusts link to some sort of detachment level in the basement (perhaps a pre-existing detachment), we have not been able to identify such a feature in the reflection seismic profiles, which reach a depth of *c.* 12 km. Thrusts cutting up from the basement breach and overprint earlier structures developed in the south Urals accretionary complex. Basement topography and faults are also the likely cause for an abrupt along-strike change in structural style from north to south.

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