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Insights into orogenesis: getting to the root of a continent–ocean–continent collision, Southern Urals, Russia

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Abstract: The Ural mountains preserve a late Palaeozoic collision that forms a 2500 km suture in the world's largest landmass, Eurasia. Several features of the mountain belt, in particular a well-preserved crustal root, are uncharacteristic of other Palaeozoic orogens such as the Appalachians and Caledonides. Previous interpretations of the Southern Uralian root suggested that it is composed of East European Craton crust derived from the west. A new potential field data model, considered in conjunction with published seismic, heat-flow and geological data, indicates that the root is composed mainly of mafic granulite, which we interpret as oceanic arc crust originally accreted from the east, subducted eastward, and metamorphosed. A load caused by crustal lateral density variations, combined with topography, isostatically compensates root buoyancy and is thus the main cause of its preservation.

Keywords: Palaeozoic, Urals, accretion, crust, roots.

The Ural mountains preserve an intact bivergent Palaeozoic collision between the East European Craton and the Siberian and Kazakhstan cratons (Ivanov *et al*. 1975; Zonenshain *et al*. 1984; Echtler *et al*. 1996; Knapp *et al*. 1996). The orogen extends 2500 km, from the Arctic Ocean to just north of the Aral Sea (Fig. 1), thus forming a major suture in the world's largest landmass, Eurasia. Several features of the mountain belt are atypical when compared with other Palaeozoic orogens such as the Appalachians, Caledonides and Variscides. In particular, in the Southern Urals, for which the most extensive geological and geophysical datasets are available for consideration of the regional tectonic history, atypical features include:

(1) a very well-preserved anomalously thick (up to 55 km) crust preserving a 12–15 km root located 50–80 km to the east of the present-day maximum topography (Druzhinin *et al*. 1990; Thouvenot *et al*. 1995; Berzin *et al*. 1996; Carbonell *et al*. 1998, 2000) (Fig. 2);

(2) assumed overcompensation of the topographic load by the crustal root (Kruse & McNutt 1988; Döring & Götze 1999);

(3) a subdued Bouguer gravity minimum, following the strike of the orogen, with an amplitude of *c*. −40 to −50 mGal; superimposed on this is a Bouguer gravity maximum of *c*. 50–60 mGal amplitude (Döring *et al*. 1997);

(4) an anomalously low terrestrial heat-flow density (20–30 mW m^{-2}) along the central axis, arc terranes of the orogen (Kukkonen *et al*. 1997);

(5) extremely well-preserved ophiolites and volcanic arc assemblages (Fig. 1) (e.g. Savelieva & Nesbitt 1996);

(6) minor syn- or post-collisional collapse in the southern part of the orogen (Brown *et al*. 1998).

When continental crust is thickened, for example, during orogenesis, it attempts to return to normal thickness. It does this either by isostatic rebound with associated uplift and erosion of upper-crustal rocks (Windley 1995) or by lithospheric extension resulting from lower lithosphere delamination (e.g. England & Houseman 1989) or crustal column gravitational instability (Dahlen & Suppe 1988; Molnar & Lyon-Caen 1988), or both. Post-orogenic extension is a key feature of many collisional orogens, e.g. Himalayas, Alps, Appalachians, Caledonides and Variscides (e.g. Dewey 1988; Nelson 1992). Such zones are generally crustal weak points and, at times, the site of later continental break-up (Wilson 1966). At the present day, some of the main Palaeozoic orogens, for example, the Appalachian and Variscides, have crustal thicknesses of 30–40 km, which are thought to be similar to their pre-orogenic dimensions (e.g. Meissner *et al*. 1987).

By contrast, the crust of the Southern Urals, as inferred mainly from seismic experiments (e.g. URSEIS), preserves a thickness that is thought to be 53 ± 2 km (Druzhinin *et al*. 1990; Berzin *et al*. 1996; Carbonell *et al*. 2000) (Fig. 2), and so has not thinned to average continental crustal thickness. Berzin *et al*. (1996) suggested that the mountains may be unusual because their collision was arrested, that is, stopped prematurely, and also because they evolved in isostatic equilibrium without gravitationally unstable high topography. They concluded that this was a result of abundant surface mafic rocks, some of which may have been incorporated into the root. Paradoxically, in their summary cross-section across the orogen, however, they showed the root to be composed of Archaean crystalline basement. In fact, several studies of the Uralian orogeny have suggested that the root is composed, at least predominantly, of Archaean East European Craton material (e.g. Berzin *et al*. 1996; Poupinet *et al*. 1997; Döring & Götze 1999). More recently, however, it has been proposed that it could comprise mafic and ultramafic rocks (Stadtlander *et al*. 1999).

We investigate the possibility that the Urals are different from other Palaeozoic orogens because of an atypical composition of the core (upper-crustal central part) and root (lower-crustal central part) of the orogen. Using geological and geophysical data we address the significance of: the composition of the core and root, their generation, and the post-orogenic evolution, regarding the atypical features of the Urals. We do this by first summarizing the present state of knowledge of the key geophy-

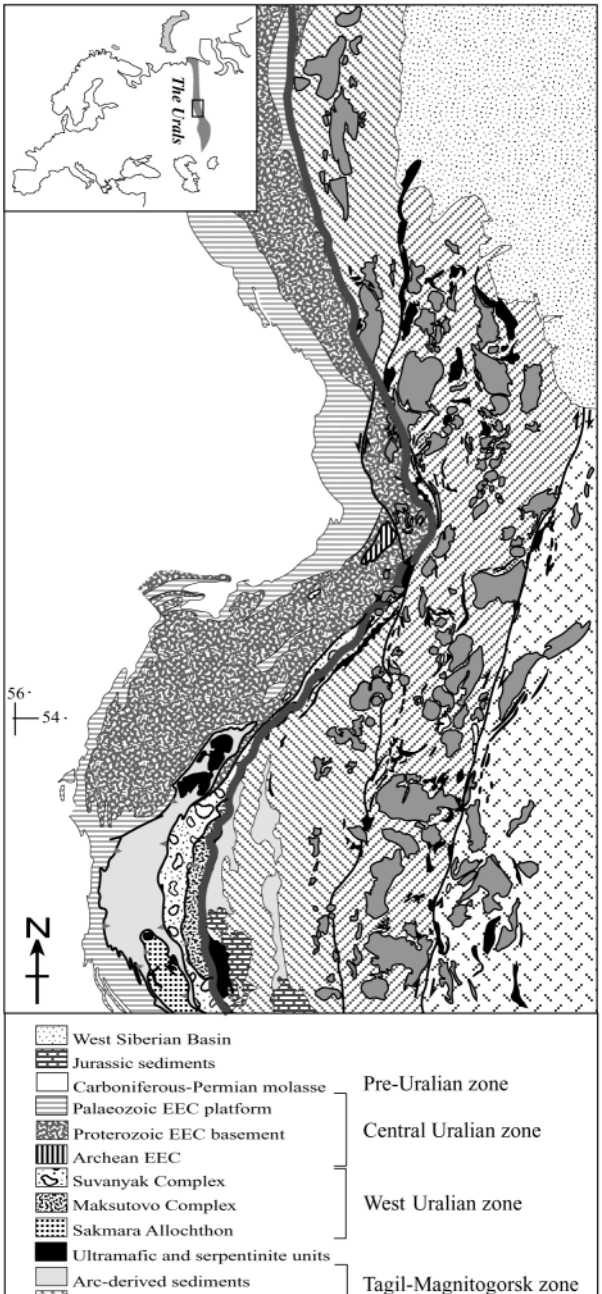


Fig. 1. Geological map of the Urals showing the geographical setting and location of the main structural units.

sical and geological properties of the main orogenic units and then considering the characteristics of the root.

Geological background

The Palaeozoic Uralian cycle began in the Late Cambrian to Early Ordovician when the eastern edge of the East European Craton rifted and a passive margin developed (McKerrow 1994; Dalziel 1997; Puchkov 1997; Smethurst *et al*. 1998). Then, through the Palaeozoic, an ocean formed as spreading followed after the rifting, and subsequently arcs, such as Sakmara, Magnitogorsk and Tagil (Fig. 1), and back-arc basins formed by intra-oceanic convergence (Zonenshain *et al*. 1984; Savelieva & Nesbitt 1996). Finally, a collision between the East European Craton, outboard arc and oceanic terranes, and the Siberian and Kazakhstan Cratons occurred in Late Carboniferous to Permian times (Matte 1995; Otto & Bailey 1995; Puchkov 1997). Together with the Appalachian, Caledonian and Variscan orogens, the Uralian orogeny contributed to the assembly of the late Palaeozoic supercontinent of Pangaea (Wilson 1966; Sengör *et al*. 1993). Notably, the Urals developed by accretion of island arcs and microcontinents (Sengör *et al*. 1993).

The Urals comprise six main structural units (Fig. 1), from west to east (Ivanov *et al*. 1975; Puchkov 1997), as follows.

(1) The Pre-Uralian marginal depression: a foreland basin filled with Lower Carboniferous–Lower Permian deeper-water marine sediments and Upper Permian molasse (Kazantseva & Kamaletdinov 1986).

(2) The West Uralian zone of Ordovician–Carboniferous shallow-deposition, continental-margin sediments and deeper-water shelf-slope sediments, and mafic volcanic rocks.

(3) The central Uralian Ural–Tau zone of Precambrian–lower Palaeozoic schists, quartzites and volcanic rocks.

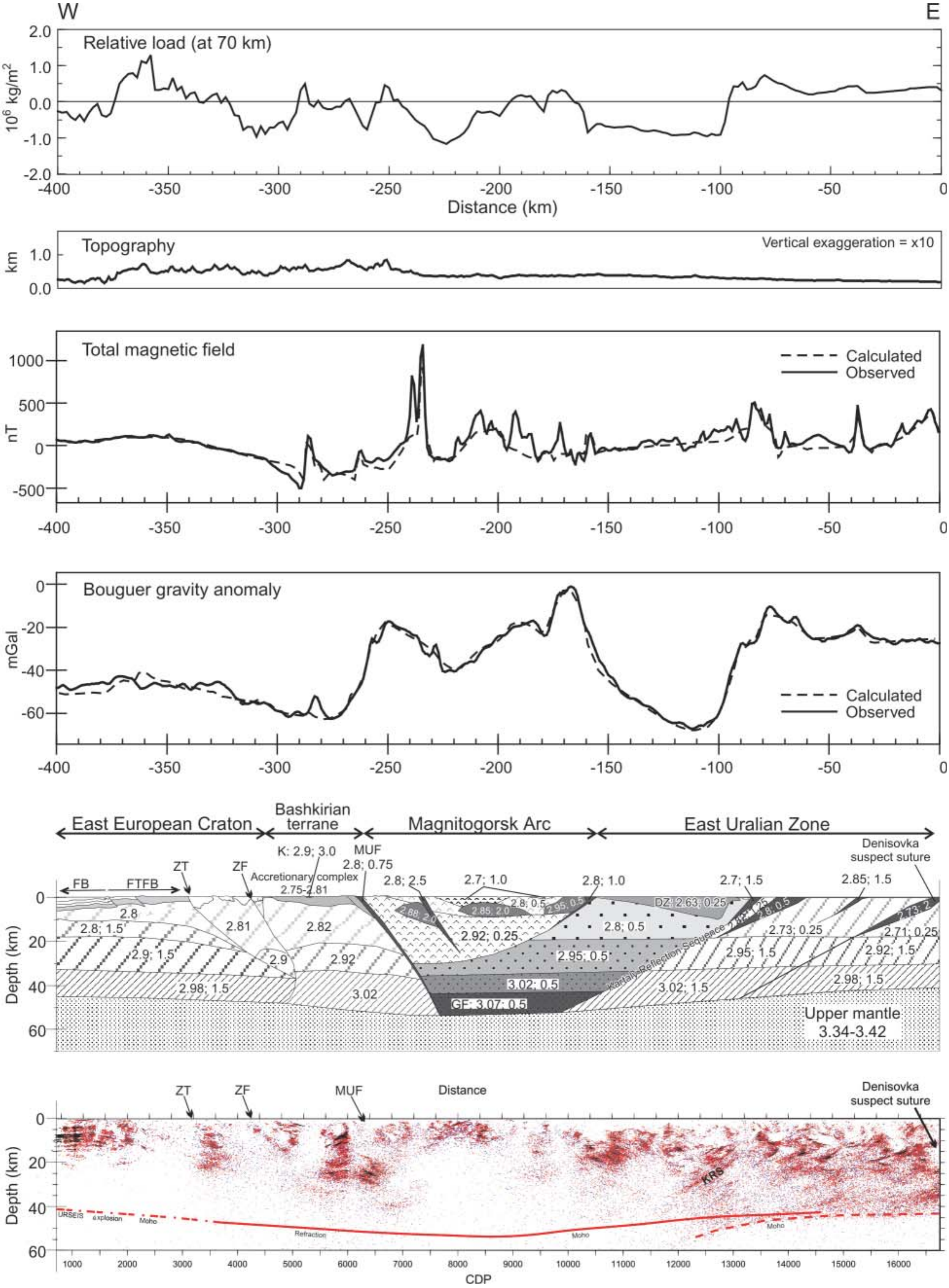
(4) The Tagil–Magnitogorsk zone, which can be divided into three sections: (a) in the NE Upper Ordovician–Devonian oceanic and island-arc volcanic rocks, with contemporaneous volcanic rocks, black cherts and shales in the NW; (b) in the centre–east harzburgite–ophiolites and centre–west zoned ultramafic–mafic complexes; (c) in the south oceanic crust, island-arc volcanic rocks and mélanges.

(5) The East Uralian zone of Ordovician–Mid-Palaeozoic volcanic and sedimentary rocks and schists, gneisses and amphibolites.

(6) The Trans-Uralian zone, the easternmost part of the Urals, where Carboniferous and Devonian calc-alkaline volcano-plutonic rocks crop out. Exposure in this region is poor, and for this reason, the eastern limit of the orogen remains controversial.

The East European Craton (units (1)– (3)) is separated from the Magnitogorsk arc (unit (4)) by the principal suture of the orogen, the Main Uralian Fault. This is a wide, east-dipping serpentinitic mélange, which, according to the seismic data, penetrates the crust to *c*. 25 km depth (Echtler *et al*. 1996). It is the main suture zone in the Southern Urals but has not experienced major post-Palaeozoic collision reactivation (Ayarza *et al*. 2000).

Fig. 2. Gravity and magnetic model for the URSEIS profile. From top to bottom: load profile at a depth of 70 km (see main text for explanation); topography; observed and calculated magnetic and gravity fields; density and magnetization model with main geological features annotated; migrated vibroseis section with the explosion Moho (left labelled dashed line) and the refraction Moho (continuous line), after Tryggvason *et al*. (2001). The numbers on the model section refer to density in Mg m^{-3}; magnetization in A m^{-1}. Where a magnetization is not shown a zero value has been assumed. FB, Foreland Basin; FTFB, Foreland Thrust and Fold Belt; ZT, Zilmerdak Thrust; ZF, Zuratkul Fault; K, Kraka Massif; MUF, Main Uralian Fault; GF, granulite-facies oceanic rocks in the root; DZ, Dzhabyk Granite. It should be noted that the root is centred beneath the Magnitogorsk arc rather than the highest topography and that magnetic, crystalline basement of the East European Craton does not project into the root zone, but ends where ZF and ZT merge in the lower crust.


W
E
Relative load (at 70 km)
10^6 kg/m^2
2.0
1.0
0.0
-1.0
-2.0
-400
-350
-300
-250
-200
-150
-100
-50
0
Distance (km)
Topography
km
1.0
0.0
Vertical exaggeration = x10
Total magnetic field
nT
1000
500
0
-500
Calculated
Observed
Bouguer gravity anomaly
mGal
0
-20
-40
-60
Calculated
Observed
East European Craton
Bashkirian terrane
Magnitogorsk Arc
East Uralian Zone
Denisovka suspect suture
K: 2.9; 3.0
MUF
2.8; 0.75
ZT
ZF
FB
FTFB
Accretionary complex 2.75-2.81
2.8; 2.5
2.7; 1.0
2.8; 1.0
2.7; 1.5
2.85; 1.5
2.8
2.8; 1.5
2.9; 1.5
2.98; 1.5
2.81
2.82
2.9
2.92
3.02
2.88; 2.0
2.85; 2.0
2.8; 0.5
2.95; 0.5
2.92; 0.25
DZ: 2.63; 0.25
2.8; 0.5
2.95; 0.5
3.02; 0.5
GF: 3.07; 0.5
Kartaly Reflection Sequence
2.73; 0.25
2.71; 0.25
2.73; 2
2.95; 1.5
2.92; 1.5
3.02; 1.5
2.98; 1.5
Upper mantle
3.34-3.42
Depth (km)
0
20
40
60
ZT
ZF
MUF
Distance
Denisovka suspect suture
KRS
URSEIS explosion Moho
Refraction
Moho
Moho
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
11000
12000
13000
14000
15000
16000
CDP

Geophysical properties and geological characteristics of the main orogenic units

Seismic data

Wide-angle reflection and refraction seismic data. Wide-angle reflection and refraction seismic data can be used to image the Mohorovicic discontinuity (Moho) and provide information on the velocity structure and physical properties of the crust. Modelling of the URSEIS (a c. 340 km long seismic profile conducted at 53°N across the Southern Urals, Fig. 1) reflection and refraction data (Carbonell *et al*. 1996, 2000; Stadtlander *et al*. 1999) reveals lateral and vertical variations in crustal velocities. The processed data show that P-wave velocities at <5 km depth have values of 5.0–6.0 km s^{-1}. Between 5 and 7 km depth, values of 6.2–6.3 km s^{-1} are typical and again fairly homogeneous across the orogen. At mid-crustal levels, 10–30 km, lateral heterogeneity is present, with the eastern and western ends of the profile (i.e. the East European Craton and the Trans-Uralian zone) having velocities of 6.4–6.5 km s^{-1}, and higher values (6.6–6.8 km s^{-1}) being present in the core of the orogen in the Magnitogorsk arc and East Uralian zone. In the lower crust, 30–55 km, the increase in velocity towards the core of the orogen is more noticeable still, being 6.7–6.9 km s^{-1} at the margins and 6.9–7.4 km s^{-1} in the root. The upper mantle is characterized by nearly uniform P-wave velocities of 8.0–8.5 km s^{-1} (Druzhinin *et al*. 1997).

Petrological conclusions deduced from P-wave velocities are non-unique because the same velocity values characterize a broad range of rock types. Uncertainties regarding lithological identification can be reduced by using both the P-wave data and Poisson ratio (σ) information (see Holbrook *et al*. 1987). However, accurate determination of σ is hampered by inaccuracies in picking S-wave arrivals so the results need to be treated with caution (Stadtlander *et al*. 1999). Carbonell *et al*. (2000) estimated σ values of >0.25 on either side of the root zone and *c*. 0.25 in the root. In contrast, Stadtlander *et al*. (1999) modelled slightly higher Poisson ratios in the root zone.

Vibroseis and explosive-source near-normal incidence seismic reflection. Near-normal reflection profiling complements wide-angle reflection and refraction data by providing high-resolution, crustal-scale images of flat-lying to moderately inclined velocity discontinuities such as shear zones and the Moho. Processing of the URSEIS vibroseis reflection data by Echtler *et al*. (1996) revealed marked differences in reflection character across the orogen and with depth. Their work permitted classification of the orogen as bivergent and division of it into three reflective domains separated by the east-dipping Main Uralian Fault and the west-dipping Kartaly reflection sequence (Fig. 2). The most pronounced reflective features of the domains are that the zones to the west and east are highly reflective whereas the central accreted terranes, e.g. the Magnitogorsk arc, are less reflective (Knapp *et al*. 1996). The highly reflective nature of the East European Craton Archaean basement is not clear in our Fig. 2, probably because the vibroseis source did not transmit enough energy through the reflective upper-crustal sequence to image the lower crust. Notably, the crustal root has a diffuse reflectivity comparable with the Magnitogorsk arc. In more detail, correlation of the data with surface geology allows controls to be placed on the deep structure of the orogenic units and the age of the reflections. In the western domain, to the west of the Main Uralian Fault, east-dipping reflectors can be correlated with imbrication of the East European Craton during both the Uralian orogeny and a Vendian event (Brown *et al*. 1998). To the east of the Main Uralian Fault, in the west of the central domain, the crust of the Tagil–Magnitogorsk zone, which, at least at shallow depths, comprises oceanic and volcanic arc rocks, is diffusely reflective. In the east of the central domain the upper crust is non-reflective down to *c*. 10 km.

The URSEIS explosive-source deep seismic reflection profiling of Knapp *et al*. (1996) provides better penetration than the vibroseis survey, allowing the detection of upper-mantle structures and clearer imaging of the Moho. Those workers estimated that the crust beneath the East European Craton and western edge of the Trans-Uralian zone is *c*. 42 km thick whereas beneath the axis of the orogen it has a (projected) thickness of up to 55 km. Furthermore, under both the East European Craton and the western edge of the East Uralian zone and the Trans-Uralian zone, the Moho is imaged as a sharp subhorizontal reflection whereas the root under the orogenic axis has diffuse lower-crustal reflectivity. Knapp *et al*. (1996) suggested that these differences resulted from real compositional variations rather than being an artefact of poor energy penetration.

Potential field data

Gravity data. The gravity response over the Southern Urals has previously been investigated by Döring *et al*. (1997) and Döring & Götze (1999). Those workers integrated quantitative gravity modelling with the velocity models derived from wide-angle experiments along the URSEIS profile and the Troitsk profile, which lies parallel to URSEIS and *c*. 55 km to the north. A positive anomaly occurs over the Archaean crystalline East European Craton. To the east the gravity low over the Bashkirian terrane (between *c*. −300 and −270 km in the profile shown in Fig. 2) is a combination of the effect of the root and the low-density material corresponding to the accretionary complex. Over the dense rocks of the Magnitogorsk zone a conspicuous feature in the Bouguer anomaly profile is a broad gravity high (located at *c*. −260 to −150 km on the profile, Fig. 2) within which a subsidiary low (centred at *c*. −230 km) coincides with a Carboniferous basin. This gravity high is superimposed on a long-wavelength gravity low of about −40 mGal, which reflects the signature of the crustal root (see Döring *et al*. 1997; Döring & Götze 1999). Further to the east of Magnitogorsk, a local gravity low (at −150 to −90 km) corresponds to the Dzhabik batholith, part of the granitic belt of the East Uralian zone (Gerdes *et al*. 2002), whereas relative highs appear to be associated with dense igneous bodies within the Trans-Uralian zone. A more detailed correlation between gravity and geology has been given by Döring *et al*. (1997) and Döring & Götze (1999).

Magnetic data. Rock outcrops and analyses of the magnetic anomaly pattern over the Southern Urals presented by Shapiro *et al*. (1997) and Ayala *et al*. (2000) provide clear evidence of magnetic, Archaean crystalline basement of the East European Craton to the west of the Urals. Similarly, magnetic basement rocks (the Kazakhstan continent and/or more magnetic allochthonous units) were inferred to be present to the east. The eastern edge of the East European Craton magnetic basement lies about 50 km to the west of the Main Uralian Fault, making it difficult to explain the modelled truncation of this basement by events relating to the Uralian orogeny (Ayala *et al*. 2000). There is, however, a closer correlation of the truncation with the Zuratkul Fault, interpreted as a possible late Proterozoic (Vendian) terrane boundary, to the west of the Main Uralian Fault. Ayala *et al*. (2000) suggested that this terrane boundary might have been influenced by the edge of the crystalline basement buttress defined by an older, early Riphean, rifting event. Short-wavelength magnetic anomalies associated with upper-crustal structures within the orogenic belt are superimposed on a longer-wavelength magnetic low. The latter is aligned along the axis of the orogen and was interpreted to be due to relatively low average crustal magnetization along this axis (Shapiro *et al*. 1997; Ayala *et al*. 2000).

Isostasy. The topography of the Southern Urals, being a maximum of *c*. 1700 m, is apparently overcompensated by the 12–15 km thick crustal root (Kruse & McNutt 1988; Berzin *et al*. 1996).

New gravity and magnetic model

Methods

In Fig. 2 we present a new gravity and magnetic model for the URSEIS profile, which reproduces the observed anomalies and provides insights into the nature of the deeper parts of the orogen. The observed fields were derived from detailed datasets provided by the Bazhenov Geophysical Expedition (Menshikov, pers. comm.). A long-wavelength regional component had been removed from the gravity field and this has been restored by comparison with a lower-resolution, unfiltered gravity dataset (Döring *et al*. 1997; Kaban, pers. comm.). Distances along the profile are relative to the origin of the URSEIS seismic reflection line, which was shot from east to west. The modelling was conducted using the GRAVMAG package (Busby 1987; Pedley 1991), in which geological bodies are represented by polygons that are assigned average densities and magnetizations. In most cases 2D geometries have been assumed, although a finite strike length has been specified where map data indicate that this is more appropriate.

Wide-angle seismic models may not fully resolve the lateral density contrasts in the upper part of the crust that are responsible for the shorter-wavelength components of the observed gravity field. Conspicuous examples of Uralian upper-crustal density contrasts are indicated by the positive gravity feature over the Magnitogorsk zone and the negative feature over the neighbouring Dzhabyk granite batholith, both of which are poorly resolved by the wide-angle seismic data. As such features have an unequivocal gravity response that can be correlated with density variations in rocks observed at outcrop, we modified the upper-crustal density structure on the basis of the observed gravity field. Densities in the deeper part of the model, 15–70 km, were calculated from P-wave velocities presented by Carbonell *et al*. (2000) and the velocity–density relationships of Barton (1986). In general, the conversion applied lay close to the ‘average’ curve of Barton (1986). The exception was in the footwall region of the Main Uralian Fault, where, in common with Döring & Götze (1999), we found it necessary to assume relatively high densities, lying close to the upper bound of Barton (1986).

On the basis of the arguments presented by Shapiro *et al*. (1997) and Ayala *et al*. (2000), it has been assumed that deep magnetic sources are magnetized in the direction of the Earth’s present field and that the lower limit for such magnetic bodies is the Moho. The Moho geometry and depth shown in the model is compatible with that presented by Skripiy & Yunusov (1989) and Carbonell *et al*. (2000).

Description

The model is effectively compartmentalized by major structures, which are assumed to extend through the crust, and it is convenient to discuss the results according to this framework. These structures are, from west to east, the Zuratkul Fault, the Main Uralian Fault, the Kartaly reflector sequence and the Denisovka suture zone (Fig. 2).

The area to the west of the Zuratkul Fault is underlain by magnetic Archaean basement. At the western end of the profile, this basement is overlain by a thick, undeformed Proterozoic–Palaeozoic sedimentary sequence, whereas moderate west-vergent deformation is evident in the Uralian foreland thrust and fold belt further east. The magnetic basement is truncated in the east at the Zuratkul Fault, but this could have occurred approximately along the line of an older, Early Riphean, extensional boundary, which may form the margin of the crystalline basement at mid-crustal levels (Ayala *et al*. 2000).

At the surface, the Zuratkul Fault juxtaposes Proterozoic units with strikingly different pre-Late Vendian deformation histories (Brown *et al*. 1996, 1997; Glasmacher *et al*. 1999). In the model, slightly higher densities are assigned to the Proterozoic metasedimentary rocks to the east of this fault to reflect their higher metamorphic grade. At greater depth this boundary accommodates both the truncation of the magnetic basement and the eastward increase in density required by the gravity model at mid- to lower-crustal depths. The implication is that the ‘Bashkirian terrane’ between the Zuratkul Fault and the Main Uralian Fault is founded on a relatively dense, non-magnetic Proterozoic basement. The allochthonous units that overlie the eastern part of this terrane were probably emplaced when the Magnitogorsk volcanic arc collided with this margin in late Devonian times.

The Main Uralian Fault is marked by a small-amplitude magnetic anomaly as a result of the magnetite content of the serpentinitic mélange it contains. On the basis of seismic evidence (Echtler *et al*. 1996) and the potential field modelling, an eastward dip of *c*. 60° has been assumed for this structure. The dip of the Main Uralian Fault is not well constrained at deeper crustal levels, but the absence of a clear seismic signature suggests that it does not become shallower at depth, and may even steepen as shown in the current model.

The relatively dense rocks of the Magnitogorsk arc are shown as a unit extending through the upper half of the crust. It should be noted, however, that the base of this unit is not well constrained by either seismic or potential field modelling, so a significantly greater depth extent is possible. Local magnetic anomalies within the Magnitogorsk zone can be correlated with serpentinite zones and magnetic plutons, some of which also have a conspicuous positive gravity effect. Further east the gravity response is dominated by a major minimum over the Dzhabyk granite, a large post-orogenic batholith that Gerdes *et al*. (2002) interpreted to have been generated as the result of partial melting of a thick sequence derived from young island-arc materials.

The lower crust between the Main Uralian Fault and the Kartaly reflector sequence lies in the central part of the root zone. It has a relatively high density and low magnetization. Its magnetization might seem surprising, considering the highly magnetic nature of some of the components of this zone, in particular the serpentinitic belts and magnetic, subduction-related plutons of the Magnitogorsk arc. However, comparison between magnetic and gravity maps and models over the Magnitogorsk and Tagil arcs indicates that highly magnetic features represent only a small proportion, $<20\%$, of these dense terranes.

The region immediately to the east of the surface projection of the Kartaly reflector sequence is the Trans-Uralian zone, an allochthonous unit made up of upper Devonian–lower Carboniferous ophiolitic and island-arc rocks (Puchkov 1997). Serpentinites and magnetic intrusive rocks along this belt give rise to short-wavelength magnetic anomalies and dense components are the source of the relative Bouguer anomaly high to the east of the Dzhabyk low. Further east, the model correlates a magnetic anomaly at the eastern end of the profile with serpentinitic rocks within the Denisovka suspect suture zone (Puchkov 1997). Evidence from the URSEIS seismic reflection experiment (e.g. Echtler *et al*. 1996) indicates that this zone dips towards the west. The upper crust between the Trans-Uralian zone and the Denisovka suture zone has a relatively low density in the current model, although this may be reduced artificially by offline effects from low-density granite plutons to the north and south of the profile. The lower crust between the Kartaly and Denisovka features is modelled with a relatively high density. Unlike the high-density zones further west, a relatively high magnetization is also required to explain the rise in the long-wavelength magnetic field towards the eastern end of the profile. The nature of the magnetic basement underlying the east side of the profile is enigmatic. The model suggests that there are allochthonous units within the Uralian orogen that incorporate a basement that is magnetic but relatively dense compared with cratonic regions. This could result from the units being microcontinental terranes whose properties have been modified by arc magmatism, or island-arc terranes with a high proportion of magnetic constituents, or their having significant volumes of lower-crustal serpentinized ultrabasic material. Magnetic basement, perhaps of the Kazakhstan continent, lies at mid- to lower-crustal depths to the east of the Denisovka suture zone. Puchkov (1997) identified a further possible suture zone, the Urkash Fault, that lies *c*. 120 km to the east of the eastern end of the model presented here, between the eastern end of the profile and the area known to be underlain by Kazakhstan basement.

Isostatic data

A load profile has been computed by summing the topographic load (above the datum) and the modelled density structure (below the datum) in a series of columns extending down to 70 km depth (Fig. 2). The density structure is defined relative to the 'background' density assumed in the gravity modelling for the 0–70 km depth interval, so the zero level in the load profile represents neutral buoyancy. The profile indicates relatively small-amplitude ($<106\ \mathrm{kg\ m^{-2}}$ or <10 MPa), short-wavelength variations about the zero level.

Discussion

Two main possibilities have been suggested for the composition of the Uralian root: Archaean East European Craton material (e.g. Berzin *et al*. 1996; Poupinet *et al*. 1997; Döring & Götze 1999) or mafic and ultramafic rocks (Stadtlander *et al*. 1999; Carbonell *et al*. 2000). In both cases eastward subduction of the East European Craton under the accreting Magnitogorsk arc from the west has been inferred as the main mechanism for incorporation of material into the root zone. From the geophysical properties and geological characteristics summarized in the previous sections and Table 1 we favour the proposal that the root is, at least predominantly, composed of mafic material.

We suggest that it is likely that a significant proportion of the root material was derived originally from the east. It could have been taken to depth by incipient eastward subduction of the Magnitogorsk arc and fore-arc associated with Mid- to Late Devonian arc–continent collision (see Chemenda *et al*. 1997), and accretion of oceanic material westward, landward, onto the edge of the East European Craton throughout the Palaeozoic (Sengör *et al*. 1993). Figure 3 presents a simple, nonunique, tectonic model that incorporates the concepts presented herein. In agreement with the proposal of accretion of oceanic material mid-crustal reflections along the URSEIS profile have been interpreted as accretion-related lithospheric stuctures (Echtler *et al*. 1996; Knapp *et al*. 1996). Furthermore, the Middle Urals westward-dipping mid- and lower-crustal fabrics have been interpreted as pre-collisional units; for example, island arcs and ocean basins underthrust from the east, with syncollisional tectonism and magmatic underplating (Juhlin *et al*. 1995, 1997). In addition, many of the East European Craton marginal ophiolites within the Main Uralian Fault zone (Fig. 1), for example, Nurali and Mindyak, comprise lherzolitic material and appear to have been preserved by incorporation into the orogen, in some cases long after their formation (Scarrow *et al*. 1999), rather than by classic obduction shortly after formation, which was the mode of preservation for a few Uralian harzburgitic massifs such as Voykar and Kempersay (Savelieva & Nesbitt 1996). Such an accretionary history would, as noted by Matte (1995), result in formation of a different core and root composition relative to the other main Palaeozoic orogens such as the Variscides (Figs. 2 and 4).

Below we outline the evidence on which our interpretation is based and discuss the implications of this proposal for each of the atypical features of the orogen outlined in the introduction.

Atypical features of the orogen

The root. Geometric considerations. Seismic experimental data (e.g. URSEIS) show the geometry of the main Uralian orogenic features, specifically, from west to east, the East European Craton, Main Uralian Fault, accreted terranes and the root (Fig. 2). The combined reflection and refraction seismic cross-section through the orogen (Fig. 2) highlights two important geometric features of the Uralian root.

First, the downward projection of the Main Uralian Fault orogenic suture separates the central and eastern part of the root from the East European Craton. Contrary to the suggestion of Puchkov (1997), based on the work of Sokolov (1992) and Petrov & Puchkov (1994), that the Main Uralian Fault might flatten at depth, we suggest that the absence of a deeper seismic expression of the Main Uralian Fault in the Southern Urals may reflect that it steepens. This geometry precludes at least the central and eastern root zone from being derived from the East European Craton basement to the west. Furthermore, truncation of the edge of the East European Craton magnetic basement at the western edge of the accreted Bashkirian terrane (Fig. 2) makes it unlikely that Archaean East European Craton crystalline basement was ever subducted beneath the orogen, let alone taken down as far as the root. In fact, the Maksutovo high-pressure complex recording subduction of East European Craton material (Hetzel 1999), which has been given as supporting evidence for the probable presence of East European Craton material in the root, records subduction of only East European Craton continental sediments, not crystalline basement.

Second, the deepest part of the root is offset to the east of the present-day maximum topography, being located instead underneath the Magnitogorsk arc (Fig. 2).

Geophysical considerations. Wide-angle reflection and refraction seismic data led Carbonell *et al*. (2000) to interpret crustal velocity variations as a result of increasing metamorphic grade and proportion of mafic material at depth. Combining Poisson ratio information with the P-wave data, they proposed that the East European Craton lower crust comprised mafic granulites (see Rudnick & Fountain 1995), but that the root consists of intermediate granulites or eclogitized granulites. In contrast, a more mafic root composition, relative to the crust on either side, was implied by the Poisson ratio modelling of Stadtlander *et al*. (1999), leading them to propose that the root may be composed, at least partially, of oceanic material.

Vibroseis reflection data indicate a variation in reflectivity

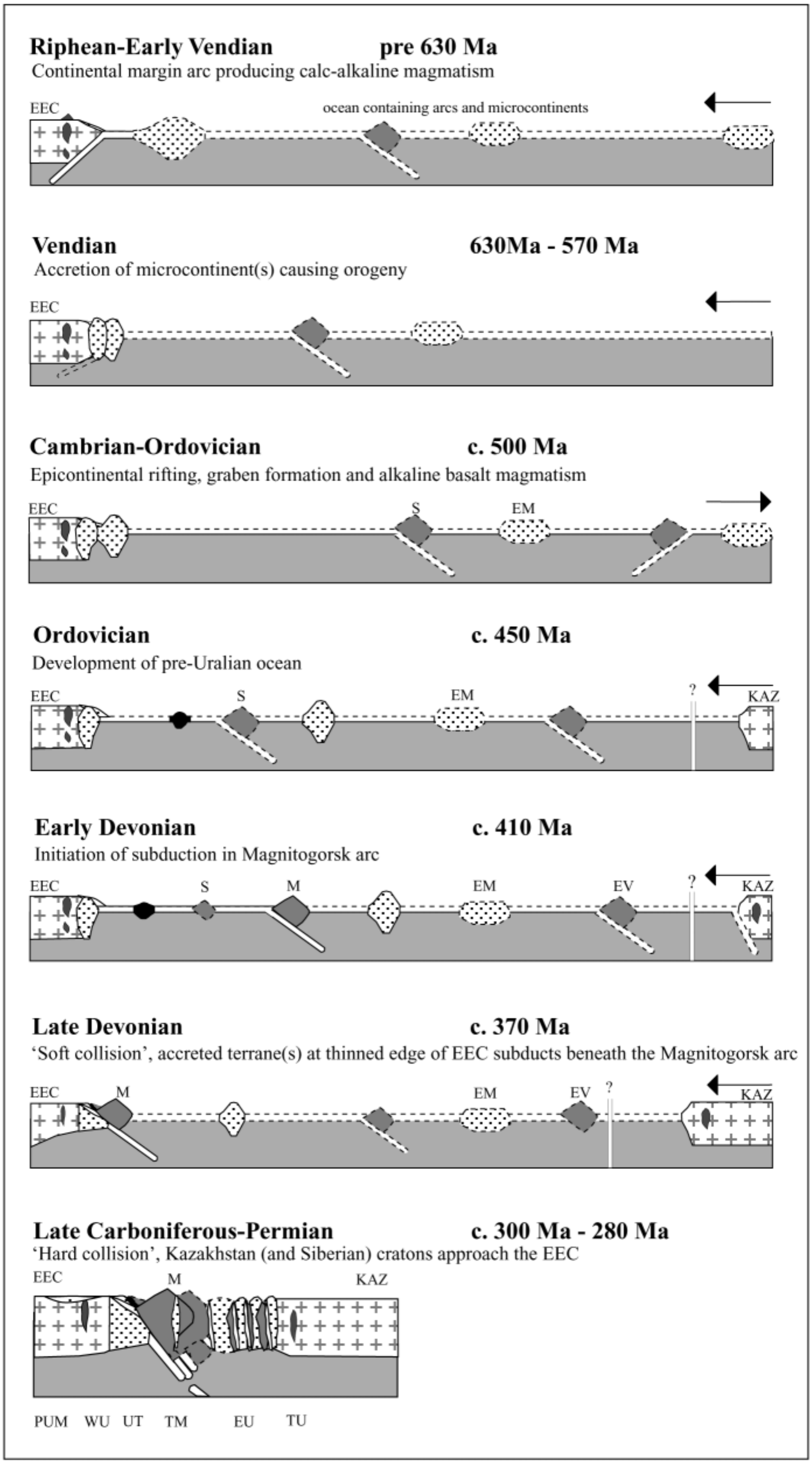
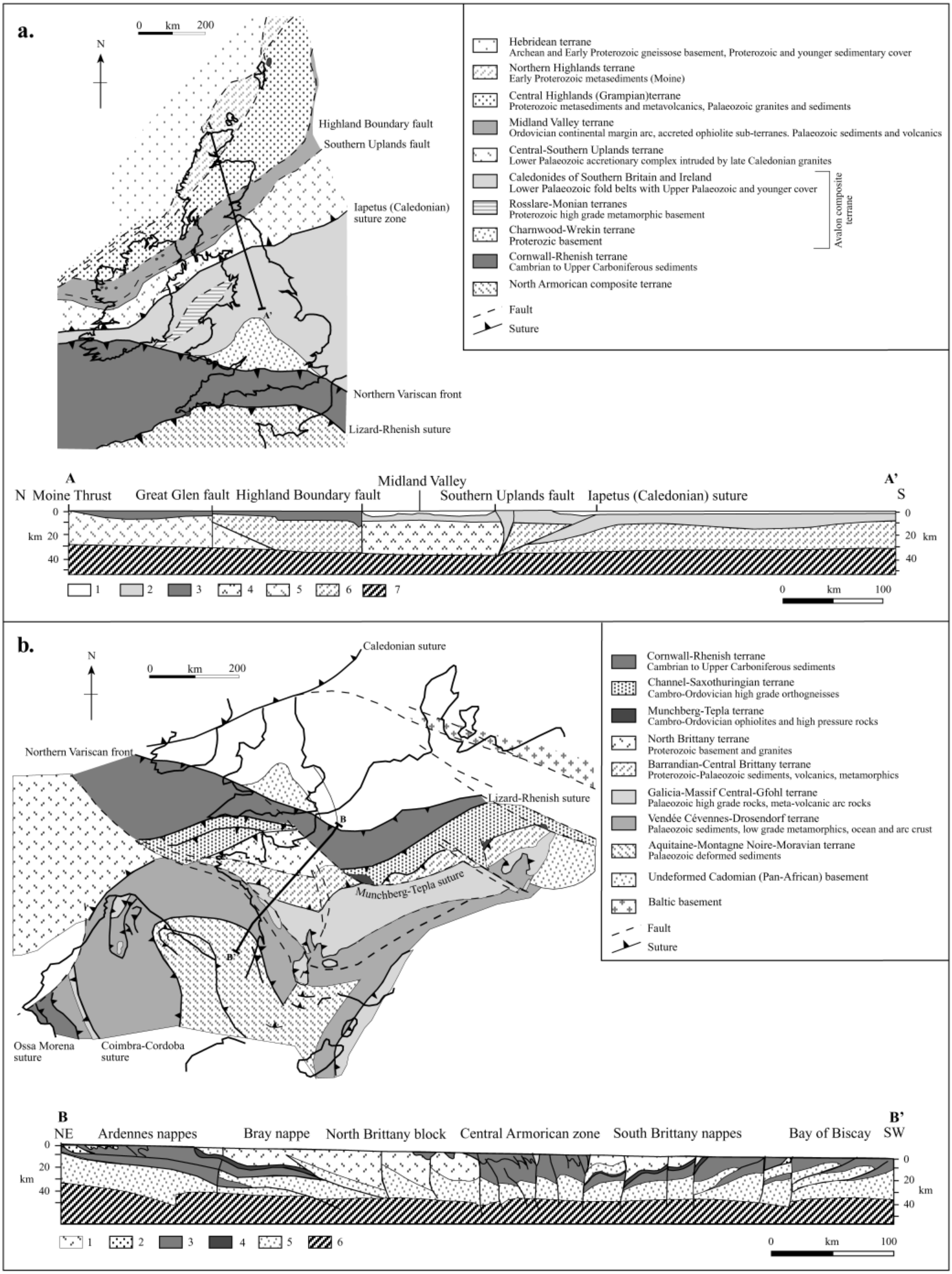


Fig. 3. Schematic Neoproterozoic–Palaeozoic tectonic evolution of the Southern Urals. Patterns: mantle (mid-grey), oceanic crust (white), arc-like oceanic crust (dark grey), mid-ocean ridge (black), microcontinents (heavy stipple), sediments (light stipple), continental crust (crosses), calc-alkaline continental plutonism (dark grey), relative distance unconstrained (double lines with question mark). EEC, East European Craton; S, Sakmara island arc; EM, East Mugodzhary microcontinent; KAZ, Kazakhstan Craton; M, Magnitogorsk island arc; EV, East Uralian volcanic subzone; PUM, Pre-Uralian marginal depression; WU, West Uralian zone; UT, Ural–Tau zone; TM, Tagil–Magnitogorsk zone; EU, East Uralian zone; TU, Trans-Uralian zone. Dashed bodies less well constrained. After Puchkov (1997).

across the orogen. The Magnitogorsk arc shallow, <10 km, crustal structure has been obliterated by voluminous, late Palaeozoic, magmatic activity associated with the waning stages of collisional orogenesis (Echtler *et al*. 1996). This has resulted in low reflectivity throughout the central part of the orogen (Knapp *et al*. 1996). For this reason Echtler *et al*. (1996) proposed that the prominent, west-dipping highly reflective Kartaly reflection sequence was formed by a late orogenic stage,


a.
0 km 200
N
Highland Boundary fault
Southern Uplands fault
Iapetus (Caledonian) suture zone
A
A'
Northern Variscan front
Lizard-Rhenish suture
Hebridean terrane
Archean and Early Proterozoic gneissose basement, Proterozoic and younger sedimentary cover
Northern Highlands terrane
Early Proterozoic metasediments (Moine)
Central Highlands (Grampian)terrane
Proterozoic metasediments and metavolcanics, Palaeozoic granites and sediments
Midland Valley terrane
Ordovician continental margin arc, accreted ophiolite sub-terranes. Palaeozoic sediments and volcanics
Central-Southern Uplands terrane
Lower Palaeozoic accretionary complex intruded by late Caledonian granites
Caledonides of Southern Britain and Ireland
Lower Palaeozoic fold belts with Upper Palaeozoic and younger cover
Rosslare-Monian terranes
Proterozoic high grade metamorphic basement
Charnwood-Wrekin terrane
Proterozoic basement
Avalon composite terrane
Cornwall-Rhenish terrane
Cambrian to Upper Carboniferous sediments
North Armorican composite terrane
Fault
Suture
A
A'
N Moine Thrust
Great Glen fault
Highland Boundary fault
Midland Valley
Southern Uplands fault
Iapetus (Caledonian) suture
S
0
km 20
40
0
20 km
40
1
2
3
4
5
6
7
0 km 100
b.
N
0 km 200
Caledonian suture
Northern Variscan front
Lizard-Rhenish suture
B
B'
Munchberg-Tepla suture
Ossa Morena suture
Coimbra-Cordoba suture
Cornwall-Rhenish terrane
Cambrian to Upper Carboniferous sediments
Channel-Saxothuringian terrane
Cambro-Ordovician high grade orthogneisses
Munchberg-Tepla terrane
Cambro-Ordovician ophiolites and high pressure rocks
North Brittany terrane
Proterozoic basement and granites
Barrandian-Central Brittany terrane
Proterozoic-Palaeozoic sediments, volcanics, metamorphics
Galicia-Massif Central-Gfohl terrane
Palaeozoic high grade rocks, meta-volcanic arc rocks
Vendée Cévennes-Drosendorf terrane
Palaeozoic sediments, low grade metamorphics, ocean and arc crust
Aquitaine-Montagne Noire-Moravian terrane
Palaeozoic deformed sediments
Undeformed Cadomian (Pan-African) basement
Baltic basement
Fault
Suture
B
B'
NE
Ardennes nappes
Bray nappe
North Brittany block
Central Armorican zone
South Brittany nappes
Bay of Biscay
SW
0
20
km
40
0
20
km
40
1
2
3
4
5
6
0 km 100

shortening event. At greater depth, in the arc domain, at 10–25 km, east-dipping mid-crustal reflectors are evident. To the east of the Kartaly reflection sequence, the upper crust is dominated by east-dipping reflectors whereas in the lower crust westward-dipping (30–40°) reflectors, which are truncated by the Kartaly reflection sequence, can, when projected surfaceward, be correlated with shear zones associated with accreted Palaeozoic oceanic material. Döring *et al*. (1997) concluded that the lack of Moho reflectivity in the vibroseis data noted by Echtler *et al*. (1996) could be related to relatively high densities (and velocities) of the root zone reducing the acoustic impedance contrast between crust and mantle.

Gravity data might be expected to reveal a major (>100 mGal) long-wavelength Bouguer gravity anomaly low associated with the Uralian crustal root. Such features are present, for example, with the crustal roots beneath the northern Swiss Alps (Klingelé & Olivier 1980) and southern Andes (Grow & Bowin 1975). Nevertheless, a major gravity minimum is not observed over the Southern Urals. This is in part because of the superimposed positive effect owing to dense upper-crustal rocks of the Magnitogorsk zone, but it also requires a density anomaly at greater depth to suppress the gravity effect of the root. In the model presented here, this is provided by lateral density contrasts at both mid- and lower-crustal levels. In the models presented by Döring & Götze (1999), the required density anomaly is provided either by a dense eclogite zone in the upper mantle beneath the base of the root (their Model 1), or by incorporating a slightly eclogitized transition zone between lower crust and upper mantle (their Model 2). To some extent the thermal low over the Urals could be implicated in generating the postulated density anomaly, the axis of the orogen being colder and therefore denser. Modelling by Kukkonen *et al*. (1997) indicated that the scale of the thermal anomaly could be up to about 50 °C over a depth extent of *c*. 50 km. Such a temperature difference is equivalent to a density anomaly of the order of 0.005 $\mathrm{Mg\,m^{-3}}$, which would contribute to the increase in density but would only be a small part of it.

The magnetic properties along the axis of the orogen are very different from those of the Archaean crystalline basement. Local magnetization contrasts, near the surface, give rise to high-amplitude anomalies along this axis but it is average crustal magnetization that is more important when considering the long-wavelength magnetic anomaly pattern. We have modelled the root with a magnetization of 0.5 $\mathrm{A\,m^{-1}}$ and the East European Craton with a magnetization of 1.5 $\mathrm{A\,m^{-1}}$. Average induced magnetization for the Archaean basement rocks of the East European Craton is in the range 0.8–3.0 $\mathrm{A\,m^{-1}}$ (Krutikhovskaya *et al*. 1979). By contrast, estimates of the average magnetization of oceanic crust summarized by Toft & Arkani-Hamed (1993) suggest significantly lower values of 0.2–0.5 $\mathrm{A\,m^{-1}}$.

From consideration of the new potential field data model (Fig. 2) in conjunction with published geophysical data, it appears unlikely that Archaean East European Craton crystalline basement is the main component of the Uralian root. The lower crust of the root zone has higher V_p, weaker reflectivity, and lower heat production, and is more dense and less magnetic than the lower-crustal Archaean basement to the west of the root (Fig. 2, Table 1). Similar property contrasts occur between the root and the lower crust on its eastern side. From our modelling it appears likely that the root is composed of a combination of rocks derived from the basement to the Bashkirian terrane, on its western side, and material of predominantly oceanic origin in its central and eastern parts. Oceanic rocks are certainly observed at the surface and are also likely to be present at depth, as is indicated by the inferred island-arc protolith to the Dzhabyk pluton (Gerdes *et al*. 2002). Notably, high-grade rocks exposed in the hinterland of the Middle Urals have been interpreted as metamorphosed Palaeozoic arc complexes (Friberg *et al*. 2000).

Geological considerations. Given the likely P and T conditions, 14–16 kbar and 600–800 °C, for a normal crustal geotherm, oceanic material at root depths of *c*. 35–50 km would be subjected to either granulite- or eclogite-facies metamorphic conditions (Yardley 1989). However, modelling of the present-day thermal regime of the Urals suggests a lower temperature of *c*. 500 °C at these depths (Kukkonen *et al*. 1997), placing the root in the eclogite stability field. Nevertheless, several lines of evidence militate against eclogite being present in the preserved Uralian root. Austrheim *et al*. (1997) concluded that eclogitization may give crustal material similar petrophysical properties to mantle material and therefore the two should not be distinguishable on seismic profiles, indicating that an eclogitic root would not be evident. Also, those workers noted that eclogites, in particular with felsic composition, are rheologically weak, relative to their granulitic equivalents. Therefore their presence produces the ideal situation for fractionation of the crust and sinking of weak dense material, with ductility enhancement by transformation plasticity or other processes, favouring delamination of the deep crust. In fact, granulites are converted to eclogites, on a geological time scale, only if water is present in the system (Ahrens & Schubert 1975). This may occur if ocean crust is hydrated as it forms and drifts away from a ridge, or water is retained in mineral phases such as phengite stable to high T and P in continental crust. The granulite to eclogite transformation may not occur if water is absent; for example, if ocean crust has been dehydrated as happens when a slab subducts. The necessity of water in forming eclogites led Austrheim *et al*. (1997) to suggest that the preserved Uralian root indicates that the fluid behaviour at depth was significantly different during its evolution compared with that in the Caledonides, where extensive fluid involvement led to widespread eclogite formation. As a result, Austrheim & Engvik (1998) proposed a dry Uralian root, in response to the work of Ryan & Dewey (1997), which outlined that residual non-exhumed orogenic root eclogites cause permanent thermal and mechanical weakening of the lithosphere, leaving it as a preferred site for continental extension and separation (e.g. the North Atlantic, which opened during the Palaeocene along the line of the Siluro-Devonian Caledonides). In agreement with the proposal of Austrheim & Engvik (1998), Leech (2001) attributed the lack of lithospheric delamination and post-orogenic extensional collapse

Fig. 4. (**a**) Terrane map of the British Isles Caledonian orogen (after Bluck *et al*. 1992; Pharaoh *et al*. 1996). Simplified cross-section: (1) Upper Palaeozoic sediments; (2) Lower Palaeozoic sediments; (3) Proterozoic sediments; (4) Midland Valley basement comprising Early Palaeozoic continental margin arc rocks and reworked Proterozoic basement; (5) Archaean basement; (6) Proterozoic basement; (7) upper mantle (Moho geometry after Barton 1992). (**b**) Terrane map of the European Variscan orogen (after Matte 1991). Simplified cross-section: (1) Variscan granitoids; (2) Carboniferous sediments; (3) Upper Proterozoic to Palaeozoic rocks; (4) ophiolitic rocks and high-grade gneisses; (5) Precambrian basement; (6) upper mantle (after Matte 1991).

during Uralian orogenesis to lower-crustal fluid-absent conditions.

Table 1 summarizes the physical properties of possible root rocks. Each of the datasets for the different rock types, with the notable exception of Archaean crystalline basement, have some properties consistent with those of the Uralian root. However, we conclude that, when considered in conjunction, the data point towards mafic granulites, with or without garnet, as being generally most similar to the root properties required by our modelling.

Assumed overcompensation of the topographic load by the crustal root: isostasy. The apparent overcompensation of the topography of the Southern Urals (maximum elevation of *c.* 1700 m and typically <1000 m) by the crustal root has been explained by invoking a dense crust or mantle load to compensate the root (Kruse & McNutt 1988). The deepest part of the root is offset to the east of the present-day maximum topography; it is beneath the Magnitogorsk arc (Fig. 2), indicating that the required additional load is also offset in this direction. The load profile for the model we present in this paper indicates that, when intracrustal density variations as well as topographic load are taken into account, there is not significant overcompensation of the topography. We therefore conclude that a high effective elastic thickness of the lithosphere does not have to be invoked to explain the preservation of the root. This is compatible with Model 2 of Döring & Götze (1999) and also with the low, 19 km, crustal effective elastic thickness estimate of McKenzie & Fairhead (1997), although the latter was based only on free-air anomalies and topography. If the density anomaly that offsets the gravity effect of the root lies in the upper mantle rather than the crust, a very rigid lithosphere is required to prevent this sinking deeper into the mantle (Döring & Götze 1999; their Model 1). Such rigidity has been predicted by McNutt *et al*. (1988) and supported by Ryberg *et al*. (1996), but is not a requirement of our model.

Subdued Bouguer gravity minimum. The subdued Bouguer gravity minimum, *c.* −40 to −50 mGal, that follows the strike of the orogen (Döring *et al*. 1997) may be explained by the lateral crustal density variations that we invoke to explain the nature of the crustal root. The amplitude of the root anomaly is reduced both because of the relatively small density contrast across the Moho and, importantly, because of a positive anomaly component generated within the crust that interferes destructively with the negative component caused by the root. The positive component includes the effects of near-surface features within the Magnitogorsk arc, so the composite anomaly takes the form of a short-wavelength high superimposed on a longer-wavelength and relatively subdued low.

Low terrestrial heat flow. The Urals have low heat-flow density ($\leqslant$30 mW m^{-2}) over a 50–100 km wide zone along the volcanic arc axis, which coincides with the root; by contrast, the adjacent cratonic areas have values of 50–70 W m^{-2}. To model the heat-flow anomaly along the Troitsk profile some 55 km north of our model section, Kukkonen *et al*. (1997) had to assume upper-crustal heat production of 0.3 μW m^{-3}, which is lower than estimated sample measurements of 0.5 μW m^{-3}. Anomalously low heat production, of 0.25 μW m^{-3} at 20–30 km and 0.1 μW m^{-3} at 30–45 km, was required at depth (Kukkonen *et al*. 1997). The heat-flow model thus contains significant lateral thermal property variations over a large proportion of the crustal thickness, inviting comparison with the physical property contrasts invoked in our potential field modelling. Consistent with this is our proposal of granulite-facies basic rocks of oceanic and island-arc origin in the root zone, which fits well with the required heat production parameters in having values of 0.1–0.4 μ W m^{-3} (Ashwal *et al*. 1987; Rudnick & Fountain 1995).

Extremely well-preserved ophiolites and volcanic arc assemblages. Throughout the Urals, ophiolites and volcanic arc assem-

Table 1. *Physical properties of Uralian orogenic units and rocks that may be present in the Uralian root*

	Uralian orogenic units			
	Root	Archaean crystalline basement	Serpentinites	Island-arc terranes
Density (Mg m^{-3})	**3.07** (1)	*2.8–2.98* (1)	2.6 (8)	**2.9– 3.3** (1)
Magnetic susceptibility (A m^{-1})	**0.01** (1)	0.016–0.06 (6)	**0.003–0.08** (9)	**0.001–0.3** (9,10)
V_p (km s^{-1})	**7–7.4** (2)	6.3–6.8 (7)	5.4 (8)	**6.8–7.8** (11)
V_p/V_s	**1.8** (2)	1.9 (2)	2.07 (8)	**1.74–1.82** (11)
Poisson's ratio	**0.25** (3)	>0.25 (2)	0.35 (8)	**0.24–0.28** (12)
Heat production (μW m^{-3})	**0.1–0.25** (4)	0.9 (4)	0.1 (4)	0.3 (4)
Reflectivity	**Weak** (5)	Strong (5)	–	**Weak** (5)

	Possible root rock types				
	Mafic granulite	Mafic granulite with garnet	Mafic eclogite	Intermediate granulite	Felsic granulite
Density (Mg m^{-3})	**2.9–3.1** (7)	**3.0–3.3** (7)	3.3–3.6 (7)	2.7–3.0 (7)	2.7 (7)
Magnetic susceptibility (A m^{-1})	**0.001–0.1** (13)	–	**0.001–0.01** (13)	–	**0.00001–0.1** (13)
V_p (km s^{-1})	**6.8–7.45** (7)	**7.0–7.5** (7)	7.8–8.6 (7)	6.5–6.9 (7)	**6.3–6.9** (7)
V_p/V_s	**1.8–1.83** (1)	**1.78–1.84** (7)	1.78 (2)	1.8–1.9 (7)	1.78 (7)
Poisson's ratio	**0.24–0.3** (7)	0.26–0.3 (7)	**0.24–0.29** (7)	**0.24–0.30** (7)	**0.24–0.28** (7)
Heat production (μW m^{-3})	**0.1–0.4** (4)	**0.1–0.4** (4)	**0.1** (4)	0.5 (4)	0.3 (4)
Reflectivity	–	–	–	–	–

Data sources are given in parentheses: (1) values used in the modelling of the present study; (2) Carbonell *et al*. (2000); (3) Carbonell *et al*. (1996); (4) Kukkonen *et al*. (1997); (5) Echtler *et al*. (1996); (6) Krutikhovskaya *et al*. (1979); (7) Rudnick & Fountain (1995); (8) Christensen (1996); (9) Carmichael (1989); (10) Milsom (1996); (11) Mooney & Meissner (1991); (12) Zandt & Ammon (1995); (13) Clark & Emerson (1991). Italic indicates properties used in the modelling of the present study; bold, properties that fall within the range of root values.

blages are very well preserved (Fig. 1). In Uralian tectonic reconstructions, it has often been assumed (e.g. Zonenshain *et al*. 1990) that one major intra-oceanic arc, Magnitogorsk (Devonian), is preserved in the Southern Urals, and another, Tagil (Ordovician–Silurian), is preserved in the Middle Urals. By contrast, from analysis of the gravity and magnetic data (Fig. 2), on which interpretation in the eastern Urals has to rely heavily because of the ubiquitous sedimentary cover, and consideration of new geochemical results (authors' unpublished work) we favour the idea, proposed by Sengör *et al*. (1993) and Puchkov (1997) and supported by Juhlin *et al*. (1998), Friberg *et al*. (2000) and Bea *et al*. (2002), that the Uralian accreted terranes may in fact host several arc systems.

It is noteworthy that in the Southern Urals, where reworking was minimal (Brown *et al*. 1998), the lateral extent of the predominantly oceanic accreted terranes is greater than either in the Middle Urals (Ayarza *et al*. 2000) or in other Palaeozoic orogens (Fig. 3), in all of which reworking was more extensive. We suggest that this difference in the composition of material forming the core of the orogen is fundamental to why the Southern Urals have evolved differently, for example, in preserving their crustal root, from other collisional orogens.

Minor syn- or post-collisional collapse in the southern part of the orogen. As outlined in the introduction, orogenically thickened crust usually returns to pre-orogenic thickness either by erosional denudation driven by isostatic rebound or by lithospheric extension, or by both (Windley 1995).

We have presented evidence, in accord with Berzin *et al*. (1996), that the Southern Urals were not in isostatic disequilibrium because the buoyancy of the root was balanced by the relatively high density of the crust. Accordingly, from detailed fisson-track studies Seward *et al*. (1997, 2002) concluded that average denudation rates for the mountain belt have been very low since the Triassic. Those workers also commented that the ages that have been least reset are those of the Tagil–Magnitogorsk zone, that is, above the deepest root.

Lithospheric extension usually results from lower-lithosphere delamination (e.g. England & Houseman 1989) or crustal column gravitational instability (Dahlen & Suppe 1988; Molnar & Lyon-Caen 1988) or plate divergence. Clearly, the preserved Southern Uralian crustal root (Fig. 2) indicates that neither isostatic rebound nor lithospheric extension has been central to the orogen's tectonic evolution. Therefore, simply, as the prerequisite crustal thinning for extensional collapse (Dewey 1988) has not occurred in the Southern Urals it is not surprising that the region demonstrates only minor effects of this process.

Summary

(1) Several features of the Ural mountains, in particular a well-preserved crustal root, are uncharacteristic of other Palaeozoic orogens such as the Appalachians and Caledonides.

(2) A new potential field data model, considered in conjunction with published seismic, heat-flow and geological data, indicates that the root is composed mainly of mafic granulite.

(3) A load caused by crustal lateral density variations, combined with topography, isostatically compensates root buoyancy and is thus the main cause of its preservation.

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