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The root of the Urals: evidence from wide-angle reflection seismics

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Abstract

The existence of a crustal root beneath the Urals which would deflect the position of the Moho by some 20 km is still largely controversial. A French–Russian project carried out a wide-angle-reflection seismic experiment across the Middle Urals to image the Moho topography along a 175-km profile running approximately east–west north of Ekaterinburg. New data show a 6-km Moho deflection beneath the central part of the orogen. The Moho reflectivity is variable along the section, with very sharp reflections beneath the Russian platform (45-km depth), and fainter attenuated signals in the root zone (51-km depth). Even if this crustal root is not as thick as indicated by some previous speculations, it makes the Urals the only Palaeozoic orogen in the world to show such a peculiarity. A major ultramafic overload in the upper crust would partly balance the crustal root, in accordance with isostatic equilibrium. We finally postulate that sharp wide-angle reflections from the Moho can be considered indicative of a layered lower crust. This would apply to the Russian platform which maybe gained this structuring during the Ordovician extensional régime.

1. Introduction

Trending north–south over 3000 km from Novaya Zemlya to the Aral Sea (Fig. 1), the Urals mark the boundary between two plates: Baltica (the Russo-Baltic plate) to the west and the Siberian plate to the east. Built during the Carboniferous–Permian (345–230 Ma), they are approximately contemporary with the Appalachian, Caledonian and Variscan belts, all testimonies of the lengthy accretion of the Pangean supercontinent during the Palaeozoic (Matte, 1986). The Uralian belt is actually part of a much broader orogen that extended along the southwestern margin of the Siberian plate — where it met the Tadzhik–Tarim plate — and also incorporated Tien Shan, Kazakhstan, Altai and Mongolia (Matte, 1995). Hence, what appears on a large-scale tectonic map as a relatively narrow and linear belt is misleading: the thick Cainozoic cover of western Siberia and the undeformed Palaeozoic sediments of Kazakhstan hide much of the orogen to the east.

The Urals are a classical obduction belt with a complex accretionary history. Unlike the Appalachians, Caledonides and Variscides, which were subsequently disrupted by the Mesozoic extension of

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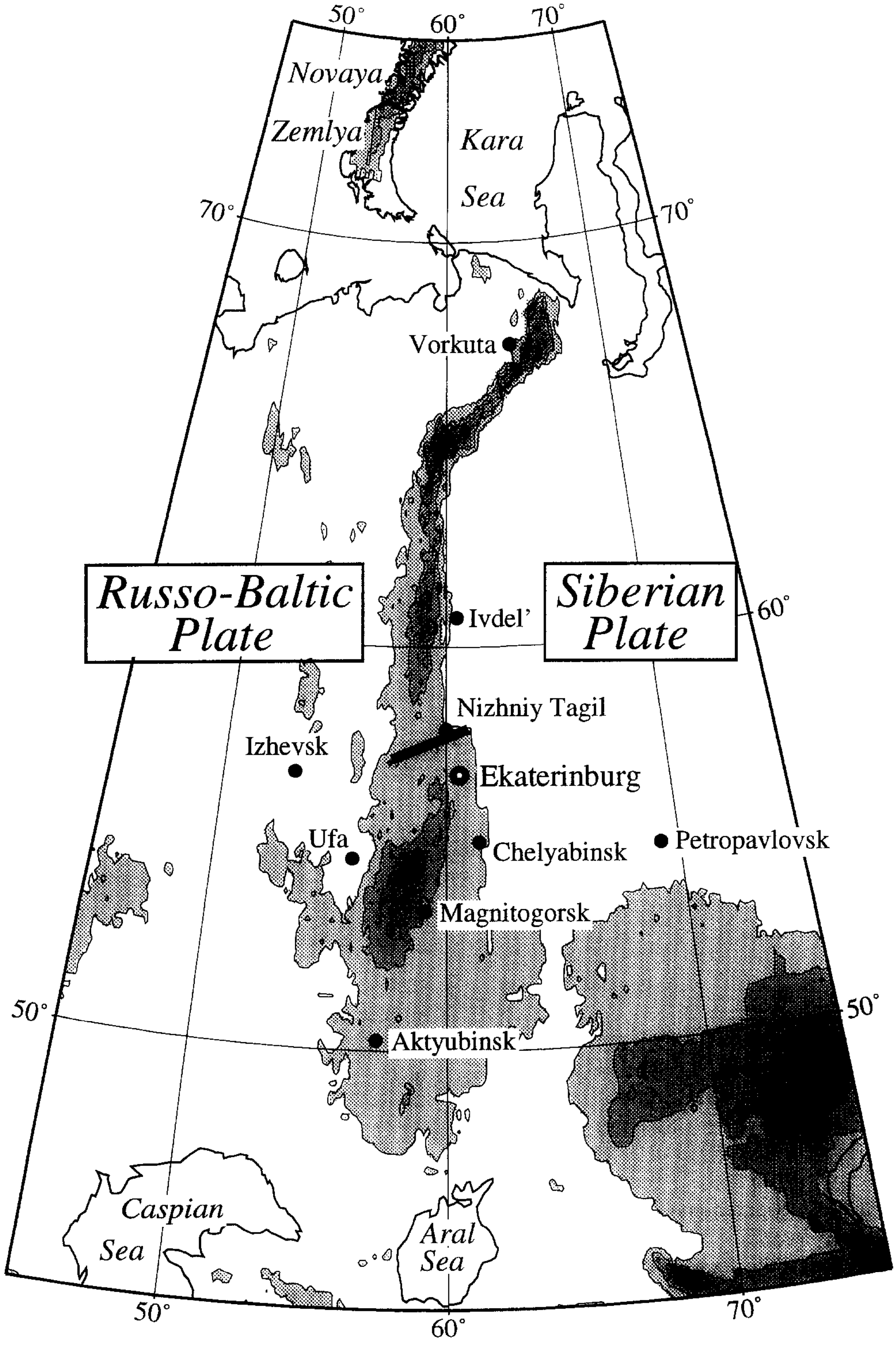

Fig. 1. Map of Central Eurasia showing the investigated area (heavy line) in the Middle Urals. Elevation higher than 200 m is shaded; maximum elevation is found in the Polar Urals, southwest of Vorkuta (1895 m), and in the Southern Urals, north of Magnitogorsk (1640 m); in the Middle Urals, maximum elevation is 500 m only.

Pangea and the Cainozoic orogeny, the Urals were only slightly reworked after the Mesozoic, and it is probably one of the best preserved Palaeozoic orogens in the world. Their early history began with Ordovician distension at the eastern margin of the Russian platform, which resulted in the formation of the Uralian ocean (Zonenshain et al., 1984, 1990). Convergence followed, first involving an eastward subduction of Baltica, and the formation of island arcs and back-arc basins. Obduction began during the Carboniferous, with a westward vergence and nappe transport from the internal (eastern) ophiolites to the external (western) Permian foredeep. This régime held till the Late Permian. A likely subduction reversal then gave the central part of the belt (Tagil–Magnitogorsk synform) its characteristic bivergent anatomy (Matte, 1995). Proterozoic and Palaeozoic terranes were partly metamorphosed and intruded by granitic domes when the continental collision occurred. The neotectonic re-activation of the belt is a long-term effect of Cainozoic uplift, with present uplift rates claimed to be as high as 2 mm yr^{-1}, and significant historical seismicity (Ryshiy et al., 1992).

The main controversy concerning the deep structure of the Urals is the existence — or the absence — of a crustal root. The Moho discontinuity is beyond doubt the major seismic boundary in the continental lithosphere, and tectonic evolution is likely to leave imprints on its position and its seismic characteristics (e.g., its reflectivity). For extensional areas in high heat-flow context, the Moho may migrate to restore a kind of lateral homogeneity. In regions of tectonic convergence and for recent orogenic belts, it is now clearly demonstrated that the Moho topography can be disrupted through dips, throws and steps, as shown in the Pyrenees (Hirn et al., 1980), the Himalayas (Hirn et al., 1984), or the Alps (ECORS–CROP Deep Seismic Sounding Group, 1989; ETH Working Group on Deep Seismic Profiling, 1991).

What happens in Palaeozoic orogens is not so clear cut. The entire crust of the Appalachians was thinned during the Late Triassic breakup of Pangea (McBride and Nelson, 1991); the Caledonides have presently a normal crustal thickness (Matthews and Cheadle, 1986) after isostatic rebound educted a 30-km-thick crustal root (Andersen et al., 1991); the Variscides have no crustal root, but the Moho reflectivity still clearly characterizes different tectonic provinces (Meissner and Wever, 1986; Matte and Hirn, 1988). If the Urals have a crustal root, as envisaged since the last decade on the ground of refraction seismic data, it would make them singular among Palaeozoic orogens. It would also bring into question the age of this crustal root — Palaeozoic, Mesozoic, or Cainozoic? The theory developed by Meissner et al. (1987), according to which crustal roots are transient and should be considered as very short-lived phenomena, might then need to be revisited. The age of the Moho deflection has maybe no influence on the persistence of crustal roots.

2. Brief review of geophysical data

The Urals have been extensively prospected for centuries because of their mineral deposits. This search has long been confined to surface observations, but a pioneer seismic profile across the belt from Ufa to Petropavlovsk was shot as soon as 1931. At present, available geophysical data address most of the area, from Novaya Zemlya to the Aral Sea. However, there is definitely a much higher coverage in the middle part of the chain between Ivdel' and Ekaterinburg (Middle Urals), and in the southern part between Chelyabinsk and Aktyubinsk (Southern Urals). Besides potential-field and heat-flow maps, these data include thousands of kilometers of deep-seismic-sounding refraction lines, most of them laid out east–west across the chain, and shorter, also E–W-trending reflection lines with a usually shallower penetration depth (10–20 km).

The Bouguer-anomaly map shows a very linear, very narrow positive high (+50 mGal in average) running along the 60°E meridian from north of Ivdel' to south of Ekaterinburg. In the Polar Urals, this gravity high trends to the northeast to join the Kara Sea. It disappears between Ekaterinburg and Magnitogorsk, only to show again in the Southern Urals with a 125-km shift to the west. On both sides of the gravity high, a long-wavelength negative Bouguer anomaly (−50 mGal) is usually found. A similar N–S-trending lineation can be observed on the aeromagnetic map.

The presence of this positive gravity high and the absence of any well-marked negative anomaly —

except in the far north (south of Vorkuta) and in the far south (Aktyubinsk region) — is difficult to understand at first glance if a crustal root is present. Druzhinin et al. (1981, 1982, 1990), Val'chak et al. (1984), Avtoneev et al. (1988) and Ryshiy et al. (1992) indeed interpreted deep-seismic-refraction data acquired since 1975 as supporting a much deeper Moho beneath the orogen ($\approx$ 65 km) than beneath the Russian platform and the Siberian plate ($\approx$ 45 km). Previous data — acquired in the 1960s — did not show such a feature, and the crustal thickness was believed to keep a constant value of $\approx$ 45 km (Aleinikov et al., 1980). In the root zone, recent interpretations include a 20-km-thick anomalous lower crust with velocities between 7.7 and 8.0 km s^{-1}. Hence, the conflict between the two interpretations — flat Moho or crustal root — boils down to identifying the top of this layer as the Moho or as an intracrustal boundary.

The Uralian gravity high is actually believed to result from high-density structures in the uppermost 15 km of the crust, with 0.10–0.15-g cm^{-3} density contrasts. These structures, which would be thin lamellae of ultramafic material vertically tectonized in the central part of the belt, produce velocity anomalies with 0.3–0.5-km s^{-1} velocity contrasts which were identified along a few seismic profiles. This mafic overload occurs in the central part of the belt (Tagil–Magnitogorsk zone), where the maximum root depth is usually found, and where heat-flow data reach an astonishing 25-mW m^{-2} low — probably a unique feature in the world. Kruse and McNutt (1988), who interpreted the compensation of the Middle and Southern Urals in terms of elastic plate bending, also concluded that a subsurface load of about 8×10^{11} N m^{-1} is necessary to get a deflection of the Russo-Baltic plate larger than 2 km beneath the orogen — a minimum value to be reached if a crustal root is detected from deep-seismic-sounding data.

3. The experiment

To test the existence of the Uralian crustal root, the simplest and probably also cheapest way is to use wide-angle seismics to record shots at a critical distance for the Moho. Corresponding reflected signals are very energetic, much more than direct waves. This technique has already been proven successfully elsewhere for such studies (Pyrenees, Himalayas, Alps).

The UWARS experiment (Urals Wide-Angle Reflection Seismics), a co-operation between the French Lithoscope programme and the Bazhenov Geophysical Expedition, Ekaterinburg (BGE), aimed at getting such a Moho profile across the Middle Urals (Fig. 2). UWARS was part of a broader experiment that Lithoscope designed with GEON Center, Moscow in the summer of 1992, when 60 stand-alone Cherepakha seismic stations were installed for 5 months along a 600-km profile which encompassed in its central part the stations shown in Fig. 2. Extending from the north of Izhevsk to well inside western Siberia, the array continuously recorded the worldwide seismicity. Inversion of P-wave teleseismic residuals is presented elsewhere (Poupinet et al., 1996). It allows an in-depth study of the Uralian lithosphere down to 250 km.

The active seismic experiment used seven shotpoints, each charged with 1.5 tonne of explosives. For each shot, five to nine boreholes were drilled, each 25–35 m deep, and seventeen recorders were spread along a 175-km profile across the Middle Urals, with recording distances between 120 and 240 km. Thirteen stations consisted of a 1.5-Hz three-component seismometer and a Cherepakha recorder with continuous analog recording. We also used four 48-channel Progress digital recorders: three channels were fed by the same kind of seismometer as above; a 1.1-km-wide cross-shaped layout and a special array of twelve 45°-tilted geophones fed the other channels. BGE had the full responsibility for the drilling, shooting and recording programmes. BGE subsequently digitized Cherepakha data, while processing mainly took place at Observatoire de Grenoble.

4. Data processing

We first processed each shot individually, with each station being positioned on the fan according to its azimuth as seen from the shotpoint. Then, to cope with the variable recording distance that prevented us from comparing reflector depths, we converted the time-dependent seismic traces into depth-dependent signals. This alternative to the usually applied normal-moveout corrections provided us with seven fan cross-sections that overlapped each other. If we do not take cross-dip into account, we can plot reflection midpoints halfway between shotpoints and stations (Fig. 2). A composite cross-section can be built along this quasi-linear common-midpoint swathe, with a zero point by 57.5°N and 57.8°E, and a strike to the east-northeast (N73° azimuth). We finally project each midpoint onto the section, where we eventually plot the corresponding depth-dependent signal. The same kind of processing can be applied whether to P-waves or to S-waves.

As this study primarily address very deep reflections, we used mean surface-to-Moho velocities for converting time scales to depth scales. Furthermore these velocities (6.50 and 3.75 $km\,s^{-1}$) are kept constant throughout the crust, which means that we overestimate depths to upper-crustal reflectors. Despite the many refraction seismic profiles that were shot across the Middle Urals, it was not so easy to do otherwise: raypaths between shotpoints and stations sample most of the tectonic units that stretch along the strike of the belt and where variations in crustal velocity are usually claimed. Besides, these variations are sometimes inconsistent, depending on authors and places of investigation. For simplicity's sake, we did not include such variations, straightforward as it would have been from the computational viewpoint. We merely checked from the literature that variations in mean crustal velocity seem to never exceed 4%, which means that errors at great crustal depth are lower than 2 km. The teleseismic experiment (Poupinet et al., 1996) also shows that, although a clear-cut lithospheric contrast is found in the western Urals, variations in mean crustal velocity never exceed a few pertiles.

A gain function is the final processing applied to the data: to balance the energy loss, amplitudes are multiplied by a factor increasing with depth. This especially enhances deep crustal reflections, but also produces slight artefacts. In some instances, ringing appears in the lower part of the seismic sections,

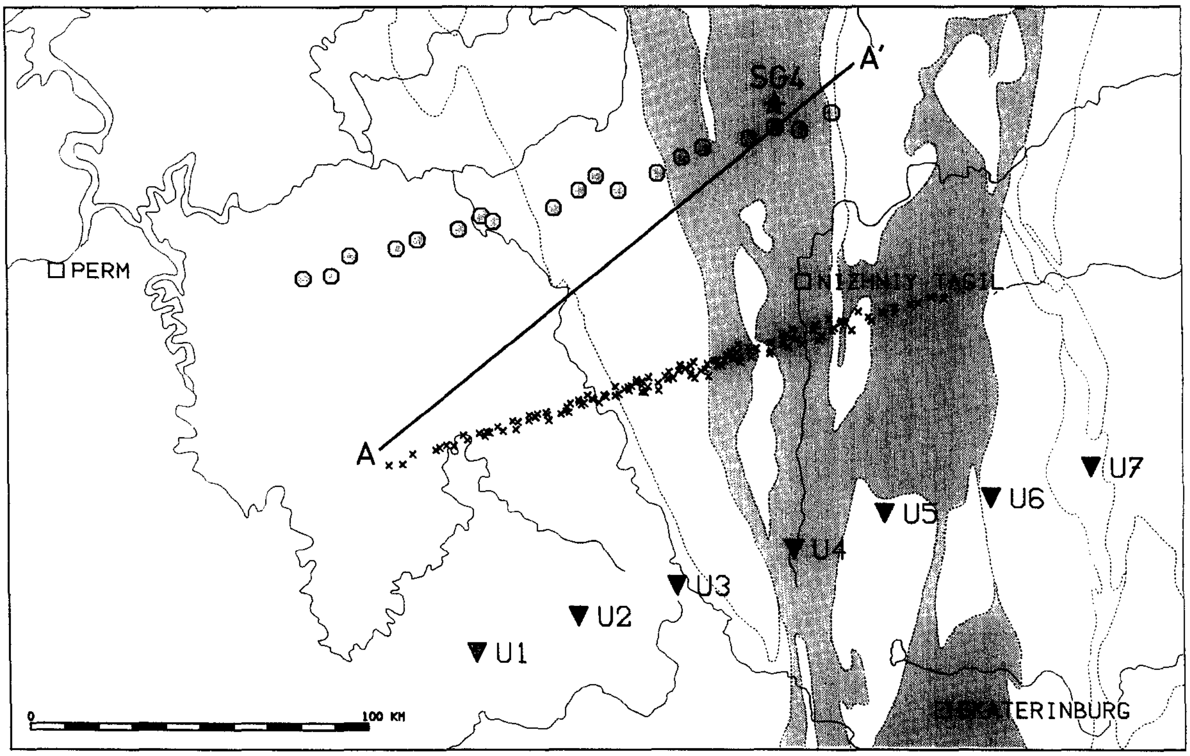

Fig. 2. Position map of the UWARS experiment. ○ = stations; ▼ = shots; x = reflection midpoints showing the position of the P- and S-wave sections (Figs. 4 and 5); shaded = Central Urals volcanogenic series; *A–A′* = position of the geological cross-section (Fig. 3) through Uralskaya Superdeep Hole (SG4).

which should not be misinterpreted as a clue to upper-mantle layering.

5. The Moho topography

The 175-km Moho cross-section samples most of the tectonic units of the Middle Urals (Fig. 3). It originates in the Russian platform, where 4–6-km-thick terrigenous sediments accumulated on the continental margin of Baltica from the Carboniferous to the Triassic. The Chusovaya River marks the boundary between this Pre-Uralian foredeep and the West Uralian zone, where the Kvarkush antiform stacks up to 20 km of very thick Riphean (Upper Proterozoic) shallow-water sediments. In the classical subdivision of the belt, the next unit to be encountered should be the Central Uralian zone, which usually forms the axial and most uplifted part of the Urals (Ural'skiy Khrebet), and is interpreted as the exhumed basement of the Russian platform. As the Middle Urals virgation virtually pinches all tectonic units, this zone is crossed here for a few kilometres only. Farther east the cross-section meets the Main Uralian Fault (MUF), a major eastward-dipping suture zone along which high-pressure metamorphism is widespread. This is the western limit of the ophiolite and island-arc assemblage of the Tagil synform, a well-preserved remnant of the Uralian ocean lithosphere. The cross-section terminates in the East Uralian zone, a complex collage of microcontinental and oceanic blocks profusely intruded by granitic magma in the late Palaeozoic.

On both cross-sections in Figs. 4 and 5, we expect the maximum amplitude of the signal to be reflected from the Moho. In the first 65 km of the section, beneath the Pre-Uralian foredeep, reflections are sharp both for P- and S-waves. The Moho depth is consistent on both sections, which simply shows that our guess of the V_P/V_S ratio (1.73) is sensible. However, a blow-up of the first 50 km of the sections (Fig. 6) shows that, although the general trend is retained, there are some minor differences in the position of the P- and S-wave Mohos. In this part of the profile, we can compute a mean Moho depth of 44.5 ± 1.5 km from P data, and 43.5 ± 1.5 km from S data. If we assume that the P- and S-wave Mohos should be identical, this difference implies a V_P/V_S ratio lower than 1.73.

Let V_P^* and V_S^* be the estimates of the P- and S-wave mean crustal velocities, V_P and V_S the true velocities, h_P and h_S the depths to the Moho as read

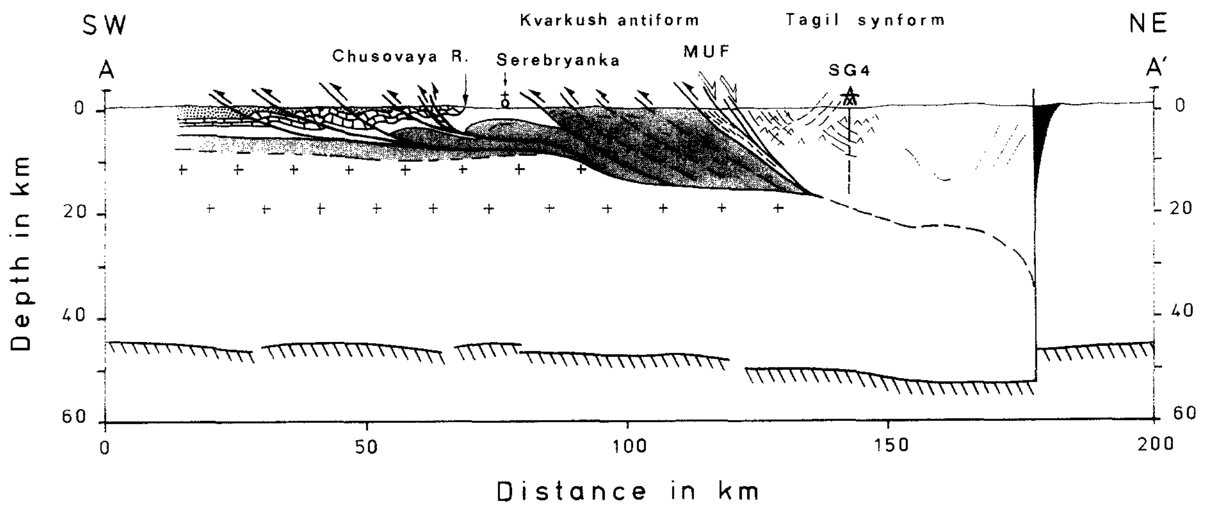

Fig. 3. Schematic geological cross-section across the Middle Urals. + = Precambrian crust; light shade = Riphean; blank = Vendian; limestone pattern = Devonian–Carboniferous; heavy shade = Permian; *MUF* = Main Uralian Fault; *SG4* = Uralskaya Superdeep Hole. Geometry for MUF and Kvarkush anticlinal stack derived from Juhlin et al. (1995). Moho topography (Figs. 4 and 5) is projected onto the geological cross-section.

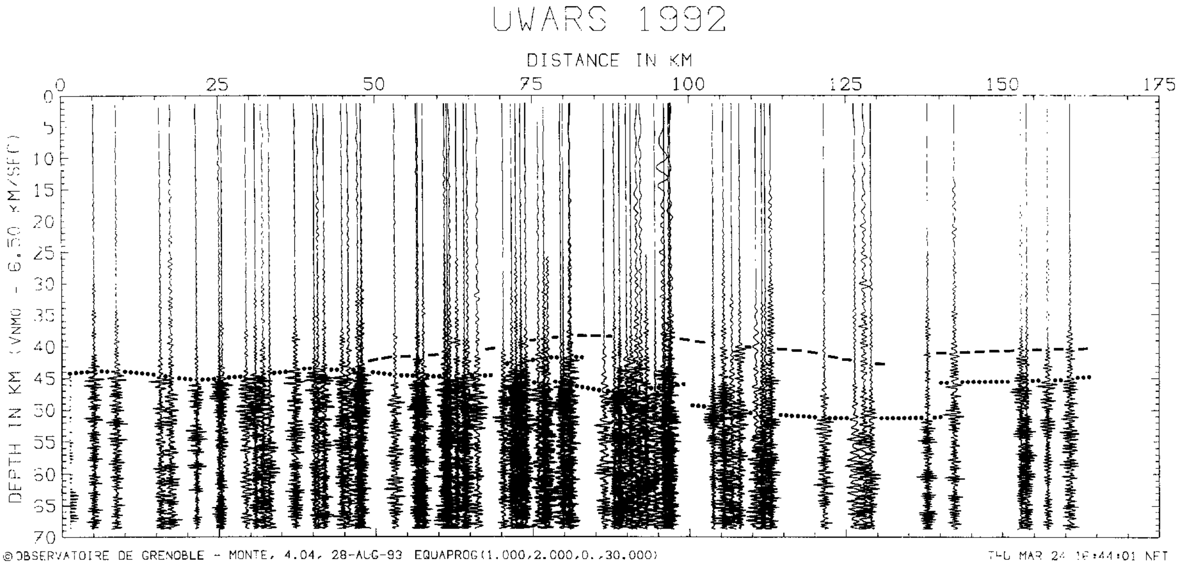

Fig. 4. West–east P-wave cross-section along the midpoint swathe (vertical component). Moho reflection is dotted and lower-crustal reflector is dashed.

from Fig. 6, and h the true depth. The difference Δh between h_P and h_S is given by:

$$\frac{\Delta h}{h} = \frac{V_P^*}{V_P} - \frac{V_S^*}{V_S}$$

and the V_P/V_S ratio by:

$$\frac{V_P}{V_S} = \frac{V_P^*}{V_S^*}\left(1 - \frac{\Delta h/h}{V_P^*/V_P}\right)$$

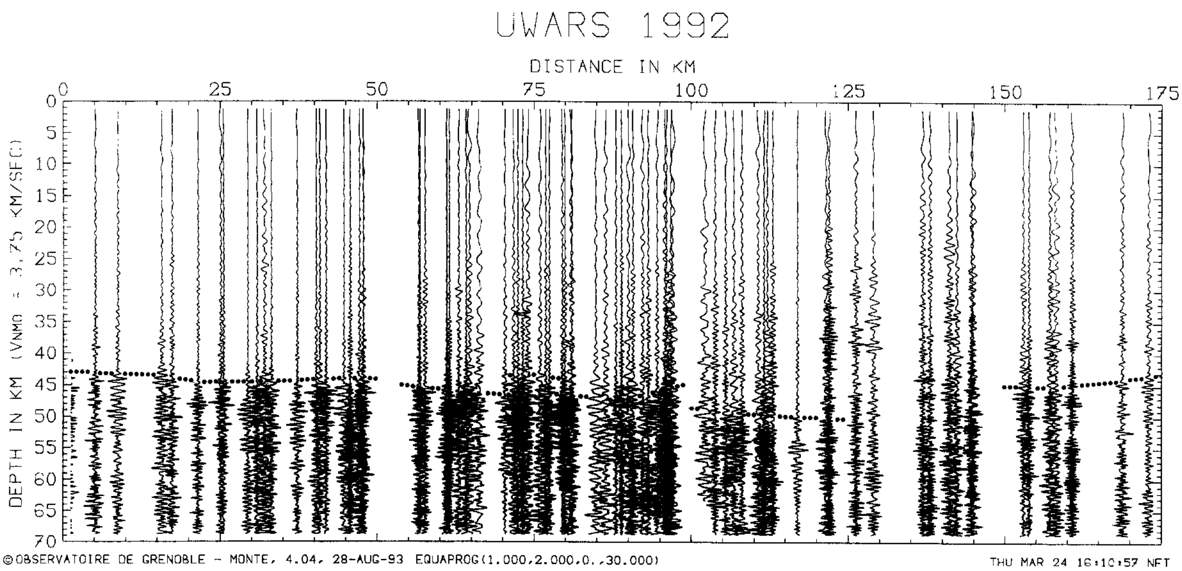

Fig. 5. West–east S-wave cross-section along the midpoint swathe (mainly transverse or radial component). Moho reflection is dotted.

If we assume that our estimate of the P-wave velocity is correct ($V_P = V_P^*$, and hence $h = h_P$), we get a V_P/V_S ratio of 1.69, which corresponds to a crustal Poisson ratio of 0.23 for the Russian platform.

Between km 20 and km 40, the P-wave Moho is

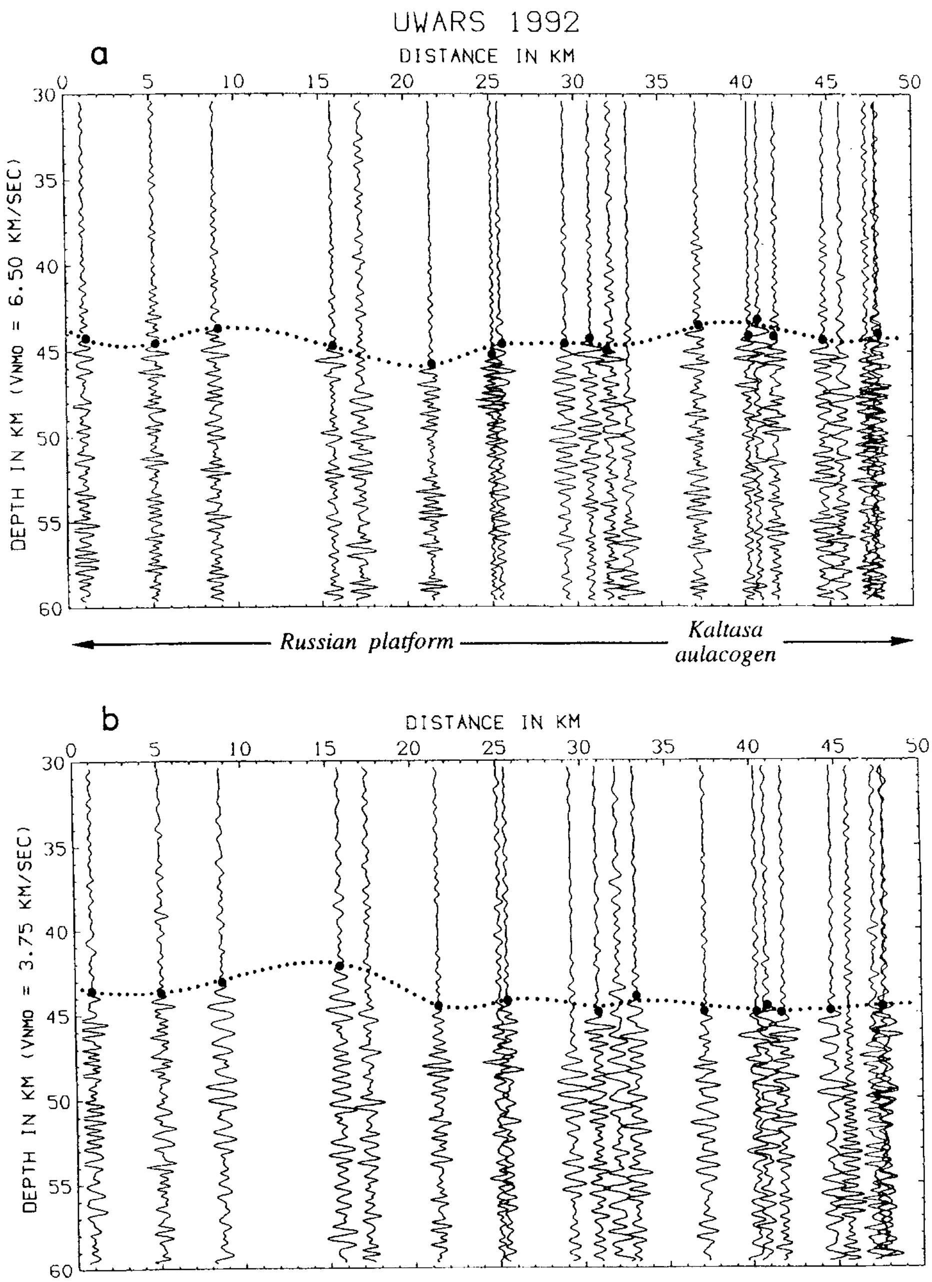

Fig. 6. Blow-ups of Figs. 4 and 5 for the first 50 km of the profile (Russian Platform). (a) P-wave cross-section; (b) S-wave cross-section Clear readings of the reflection from the Moho shown by ●.

also slightly undulated (Fig. 6a). The amplitude of this undulation is ± 1 km — or $\pm 2\%$ if we refer it to the mean Moho depth, with a low at km 20 and a high at km 40. Ascribing this undulation to velocity changes implies a corresponding $\pm 2\%$ variation. This is, however, unlikely: signals plotted around km

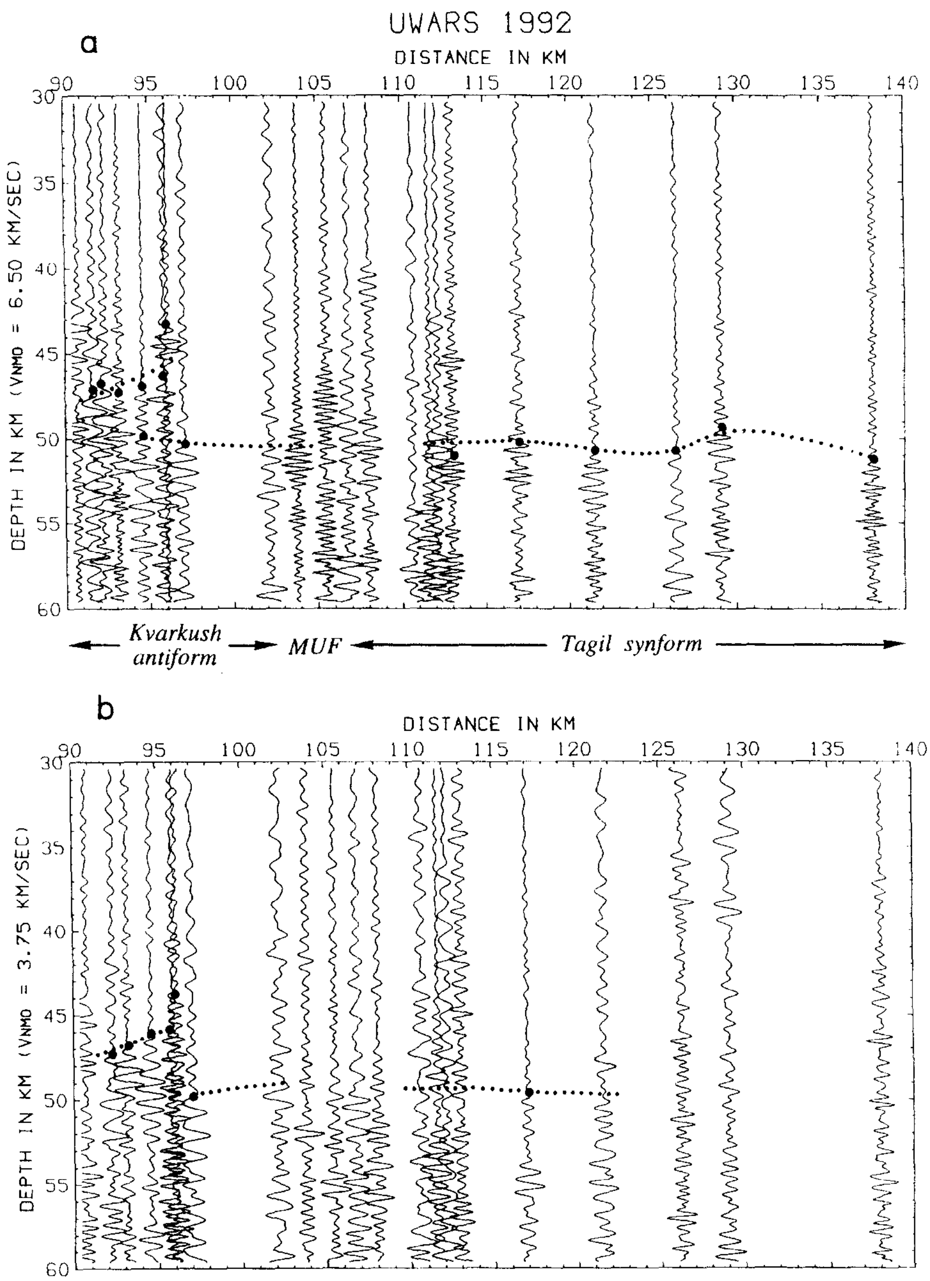

Fig. 7. Blow-ups of Figs. 4 and 5 between km 90 and km 140 (root zone). (a) P-wave cross-section. (b) S-wave cross-section. Clear readings of the Moho reflection shown by ●. The root zone is best imaged on the P-wave cross-section (a). Between km 100 and km 115, where the profile crosses the Main Uralian Fault (*MUF*), the Moho has a very poor reflectivity.

40 correspond, for instance, to raypaths that originate in shotpoints U1, U2, or U3 (Fig. 2), and propagate in the crust of the Russian platform along azimuths ranging from N45°W to N20°E. This eventually rubs out the effect of any seismic velocity anomaly. For the same reason, we can exclude the pull-down or pull-up effect which would result from variable sediment thickness under the stations. The Moho undulation, slight as it is, is therefore not an artefact. A possible interpretation for this topography is the presence of the Kaltasa aulacogen, a 500-km-long, NW–SE-trending graben that formed during the Riphean southeast of Perm' (Aleinikov et al., 1980). Aeromagnetic data also clearly show this deep-seated feature of the Russian platform.

At km 70 the profile enters the West Uralian zone. The Moho is clearly shifted upwards by 3 km. It farther resumes its previous position (46 km). From km 85 onwards — which corresponds to the central part of the Kvarkush antiform — Moho reflections are less and less clear, whether on the P-wave or S-wave sections. Another blow-up of Figs. 4 and 5 for this part of the profile where wave correlations can be critical is represented by Fig. 7. Even trying to pick the maximum amplitude of the signal proves uneasy. However, comparing the P- and S-wave sections in Fig. 7 is helpful, especially at places where signals get suddenly clearer and show consistent features. This is, for instance, the case between km 90 and km 95, where the 47-km-deep Moho shows a local westward dip. At km 97, a deep reflection is very clear from the P data (50.5 km) and the S data (50 km).

Along the next 15 km — between km 100 and km 115 — the profile crosses the MUF. The presence of reflected energy on both P and S sections in the 45–50-km depth range suggests whether a local change of the Moho to a broad second-order discontinuity, or possible diffractions from the continuation of the MUF at depth. This zone with a poor Moho reflectivity is located right beneath the emergence of the MUF in surface; the geometry of the MUF, derived by Juhlin et al. (1995) beneath the Tagil synform as a low-dip fault, might be actually more complex than what is shown by Fig. 3.

The rest of the root zone is only clearly conspicuous from the P data (Fig. 7a), between km 115 and km 140, beneath the Tagil synform. A maximum depth of 51 km is reached beneath the eastern edge of this unit, some 20 km south of Nizhniy Tagil.

Reflected signals get sharper farther east when the profile enters the East Uralian zone (km 140). Even if the data quality does not allow us to derive a clear-cut geometry, the Moho topography seems to be suddenly disrupted, both on the P-wave and S-wave sections (Figs. 4 and 5), and the Moho returns to depths around 45 km. The quality of the reflections is definitely degraded in comparison to what is observed beneath the Russian platform.

The P-wave section also shows what could be interpreted as an intracrustal reflector a few kilometres above the Moho (Fig. 4). The lower crustal layer sandwiched in between has a maximum thickness of ≈ 10 km in the root zone. It tapers to the west and disappears at km 50, approximately where the profile leaves the orogen and enters the Russian platform. This intracrustal reflector does not show up on the S-wave section.

6. Discussion

Even if the crustal root is not as thick as indicated by some previous speculations, it makes the Urals the only Palaeozoic orogen in the world to show up such a peculiarity. Besides, logistics drove us to investigate the Middle Urals, maybe a rather atypical topographical saddle zone with elevation lower than 500 m. The root is maybe much more salient in the Southern Urals or in the Polar Urals where elevation culminates over 1600 m.

It is not clear at first glance if one should consider the crustal root as a relic of the Palaeozoic collision. It could also be a post-Uralian feature related to neotectonics events. There are some clues that present seismicity in the Middle Urals is caused by an overall E–W-oriented compression in the middle of the Eurasian plate. The Cainozoic uplift could result of this compression, together with a corresponding down-buckling of the crust — and maybe of the whole lithosphere.

The age of the crustal root can best be discussed using morphological considerations. Although the Moho topography in the root zone is not well imaged — because the Moho lacks reflectivity in places and/or because diffractions from deep faults possibly blur the data — there is some clue to the asymmetry of the root. Especially, the sudden reduction in crustal thickness beneath the East Uralian zone gives one the impression that a very different eastern crustal block is juxtaposed with the Uralian collage. If the Cainozoic uplift were the result whether of the eduction of the crustal root or of the E–W-oriented compression, we would expect to find a maximum elevation in the eastern part of the Tagil synform, where the maximum Moho depth is found. This is not the case, since the maximum elevation is in the Central Uralian zone, west of the MUF. This root asymmetry and this shift to the east are two clues to considering the root as a remnant of the Palaeozoic continental subduction.

The BABEL experiment in the Baltic shield (BABEL Working Group, 1990) revealed the existence of a 10-km crustal root beneath the Svecofennian Precambrian belt, which was thus preserved for over 1.85 Gyr. Also built during Palaeoproterozoic, the Trans-Hudson orogen in Canada shows a 6–9-km crustal root, imaged in an unprecedented picture of ancient crustal accretion (Lewry et al., 1994). The 6-km crustal root detected beneath the Urals — though much younger than the two previous cases — is still another example of the possibility for crustal roots to survive post-collisional processes over a long span of time (230 Myr in the case of the Urals). Metamorphism, material transfer, and magmatic intrusions occurring at the crust/mantle boundary, as well as post-collisional collapses would therefore be unable to alter the Moho topography, at least in some specific cases.

It is sometimes argued that the disappearance of crustal roots is a non-problem, in the sense that steady crustal roots would build up only beneath orogens where a continental subduction occurs, and not elsewhere. This would hold for the Variscides and the Appalachians (no continental subduction, no steady crustal root), and for the Trans-Hudson orogen and the Urals (continental subduction, steady crustal root); but not for the Svecofennides (no continental subduction, steady crustal root), nor for the Caledonides (continental subduction, no steady crustal root).

Yet, in the Urals, the presence of a major ultramafic overload in the upper crust partly balances the crustal root, in accordance with isostatic equilibrium. This was already recognized by Kruse and McNutt (1988), although the depth of the load played no role in their models. (It was only referred to as a "subsurface load".) Besides the fact that no post-collisional extension occurred, the root *cannot* disappear because the high crustal density requires some buoyancy underneath. The preservation of a crustal root would therefore depend on the orogenic cycle allowing a large subsurface overload. In this view, we could even predict that a very likely candidate for preserving a crustal root would be the western Alps, where mantle slices imbricated in the upper crust presently deflect the Moho by some 20 km — a situation rather similar to that of the Urals.

Comparing the Urals and the Alps leads us to a final general observation concerning the change in Moho reflectivity from the foreland to the root zone. Clearly, reflections beneath the Russian platform (Fig. 6) are different in shape and pattern from those in the root zone (Fig. 7) or in the East Uralian zone. Long et al. (1994) state that wide-angle reflections — from the Moho or from an intracrustal boundary — result from a concentration of lamellae, and should not be considered indicative of sharp velocity discontinuities. This is probably not the case anywhere, but we can go one step farther in postulating that *sharp wide-angle reflections from the Moho are clues to a layered lower crust.*

Such *sharp* wide-angle reflections can be observed in the foreland of both the Urals and the Alps (ECORS–CROP Deep Seismic Sounding Group, 1989). They usually have a frequency content of ~ 10 Hz, much higher than reflections from the root zone; their onset is clear; the waveform is rather simple (limited to a few wiggles). In the Alps, near-vertical reflection seismics showed how reflective and layered was the lower crust of the foreland (Mugnier and Marthelot, 1991; Sénéchal and Thouvenot, 1991). Wide-angle reflection seismics failed to image this layering because they purposefully addressed a deeper level, and above all because a stack of thin lamellae with an alternation of high and low velocities is transparent to wide-angle observations (Thouvenot et al., 1990).

The sharpness of wide-angle reflections from the Moho beneath the Russian Platform makes us speculate that the lower crust is layered and consists of very reflective lamellae. Ascribing this layering to crustal extension (Mooney and Meissner, 1992) would be consistent with the Ordovician distension that elongated the eastern margin of Baltica at the beginning of the Uralian orogenic cycle. New data will hopefully come out in the vertical-reflection seismic transect that the Europrobe programme has scheduled across the Urals. It will no doubt be a challenge to image the root zone, where the lower crust and the Moho will probably lack reflectivity, but very reliable data can be expected in the foreland crust.

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