A model of Palaeozoic obduction and exhumation of high-pressure/low-temperature rocks in the southern Urals

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Abstract

A new evolutionary geodynamic model of Devonian continental subduction and exhumation of high-pressure/low-temperature metamorphic rocks in the southern Urals is proposed based on the results of physical modelling, geological and geophysical data, and on the comparison of this belt with other orogens. The model includes the following principal phases. (1) Closure of the western Uralian ocean by eastward intraoceanic subduction associated with the Magnitogorsk volcanic arc. (2) Subduction of the European continental margin, causing failure of the overriding plate in the arc area along a fault dipping eastward under the arc. (3) Subduction into the mantle of the fore-arc block together with the underlying continental crust and sedimentary layer. The sedimentary cover, as well as the crustal and mantle fragments of this block, are scraped off and accreted in front of and under the arc. The continental crust, shielded from the hot mantle by the fore-arc block, subducts to depths of more than 150 km, remaining at a relatively low temperature. The crust then fails at depths of several tens of kilometres. (4) The subducted crustal slice starts to rapidly rise and intrude the interplate zone, scraping and pushing up the sediments and slivers of the oceanic fore-arc block previously dragged down to different depths. (5) Exhumation of the rising high-pressure/low-temperature rocks within the Uraltau dome, separating the subduction accretionary complex from the Magnitogorsk arc. The eastern border of the Uraltau dome coincides with the Main Uralian Fault. This fault represents a complex suture zone which at the stage of deep crustal subduction was associated with a major thrust (subduction) fault, and at the exhumation stage with a major normal fault corresponding to the upper surface of the rising crustal/sedimentary body.

Keywords: Urals; continental subduction; exhumation; orogenesis; arc–continent collision; obduction

1. Introduction

Modern studies of high-pressure/low-temperature (HP/LT) rocks in many orogenic belts (Chopin et al., 1991; Dobretsov, 1991; Sobolev et al., 1992; Okay, 1994) has resulted in a new pulse for the investigations of collision and obduction, and prompted a reconsideration of previous models for these processes. It seems to be generally assumed now (Dobretsov, 1991; Wheeler, 1991; Hodges et al., 1992; Aviad, 1992; Michard et al., 1993; Boyle et al., 1994; Ernst...
that both the burial of the continental crustal/sedimentary rocks and at least part of their rapid exhumation from great depths occurs during plate convergence and orogenesis. Exhumation of HP/LT continental rocks containing coesite implies that continental crust can be subducted to depths of at least 100 km. Actual depth of continental crust subduction may be considerably greater, because the metamorphic rocks which reached the surface may represent only the upper part of the uplifted continental material. There is now also a near-consensus that the major force driving the exhumation of high-to ultrahigh-pressure rocks is the buoyancy force exerted on the low-density crustal material subducted to great depths (Dobretsov, 1991; Ernst and Liou, 1995). Analysis of the available data in different collisional belts reveals large structural and metamorphic differences between them, although most contain clear evidence of continental subduction. Subduction and exhumation of continental material appears to be a basic process of orogenesis, although it is still poorly understood.

The way to try to understand the mechanics and physics of continental subduction is to perform quantitative modelling (either experimental or mathematical) of this process. Modelling can define physically possible scenarios (or physical limits on the possible models), but cannot provide a definitive model because many of the physical parameters characterizing the prototype are unknown or poorly constrained. The possible geodynamic models obtained by modelling must be tested against observation. One cannot perform a comprehensive test based only on a single orogen, as the available regional information is very limited. Ideally, the test should involve all the collisional belts corresponding to different evolutionary stages and conditions of continental subduction. In this paper we use the data on the Urals to test and to further develop the models already tested in other regions.

Based on the results of physical modelling, Chemenda et al. (1995, 1996) have developed a model for continental subduction and defined two principal modes for this process corresponding to a low compressional regime (LCR) and a high compressional regime (HCR) of continental subduction. The regime is controlled by the total pull force from the subducted lithosphere, which in turn depends on many poorly constrained parameters such as densities (and their change due to metamorphism) of the lithospheric layers, strengths and thicknesses of different layers and others. In both regimes the continental crust can subduct to a great depth, 150–200 km or more. The crust then fails under the buoyancy force. The principal difference between the regimes is the location of the failure. In the HCR the crust fails near the front of the subduction zone, while in the LCR the failure criterion is fulfilled at a depth of several tens of kilometres. Failure is followed by a rapid buoyancy-driven uplift of the subducted crustal slice and exhumation of its upper part. This process is different for the two regimes. Both models were tested in different regions and the conclusion was that two regimes of continental subduction probably exist in nature. The HCR corresponds fairly well to the Miocene evolution of the Himalayas, while LCR is representative of the situation in the Oman Mountains (which resembles very much the southwestern Urals) and probably can be applied to other orogens where high- to ultrahigh-pressure rocks outcrop. Based on this similarity Matte and Chemenda (1996) have applied the LCR model of continental subduction to explain exhumation of the Maksyutovo high-pressure metamorphic complex in the Urals. While generally consistent, the proposed model (as all the previous models for the deep continental subduction and exhumation) does not take into account the arc-continent collision preceding exhumation. We first believed that arc-continent collision does not affect deep subduction and exhumation of the continental crust. However, further analysis of the situation in the Urals, in the view of physically possible options for the arc-continent collision, has shown that this process can play a fundamental role. One of the modes for arc-continent collision, obtained by the physical modelling, includes a failure of the overriding plate in the arc area and underthrusting of the fore-arc block under the arc. This block can subduct completely into the mantle together with the underlying continental crust, providing thermal insulation of this crust. The continental crust subducted to great depths and preserved between the cold fore-arc block and the mantle layer of the subducting plate is kept at a relatively low temperature. This process is an essential element of a new model presented in this paper, which explains...
in particular the low peak temperature (550–600°C) reached by the rocks of the Maksuyuto complex metamorphosed at a depth of several tens of kilometres (17–25 kbar; Dobretsov, 1991; Lennykh et al., 1995).

2. Tectonic overview of the southwestern Urals

The Urals are a 3000 km long, N–S-trending Palaeozoic mountain belt which separates Europe from Asia. The western part of the southern Urals, from the Permo–Carboniferous foredeep to the Main Uralian Fault, is characterized by west-vergent thrusting (Fig. 1). Thrusts are well defined by drilling in the Permo–Carboniferous foredeep basin (Kazantseva and Kamaletdinov, 1986) and by structural analysis in the Bashkir anticlinorium (Brown et al., 1996) where variably metamorphosed Riphean sedimentary units are stacked together with Vendian–lower Palaeozoic sediments. Westward thrusting is also clearly revealed in this area by the new URSEIS vibroseis and explosion-source deep reflection profiling (Echtler et al., 1996; Knapp et al., 1996) which images the deep structure of the crust down to 20 s TWT (approximately 60 km). In the Bashkir anticlinorium, east-dipping reflectors clearly cross-cut the bedding of the Vendian and Riphean series. Further to the east, large (500 km long and 20–50 km wide) allochthonous units (ophiolites and flysch) are preserved in the Zilair synform. The root of these oceanic mantle klippes is located 30 km to the east along the Main Uralian Fault where various slices of ultramafic rocks and even some large ophiolitic massifs like the Nurali massif outcrop. The lower Zilair unit consists of a thick (up to 5000 m) Devonian and older flysch, characterized by detrital spinels (Kazantseva and Kamaletdinov, 1986). This flysch unit is allochthonous and overrides shallow marine Ordovician to Devonian sediments. In the southern section (Fig. 1B), the whole sedimentary pile is tightly folded with a steep fan-like cleavage. The upper 2000 to 3000 m thick synformal unit (Kraka and Kimpersai ophiolitic klippes) consists mainly of ultramafic rocks (Savelieva and Pertsev, 1995) with a sole of serpentinites and a few basalts and gabbros. Folding and cleavage of this allochthon are supposed to be Late Permian, contemporaneous with thrusting within more external units. Emplacement of the Zilair allochthon itself probably occurred earlier, during the Carboniferous.

One of the most remarkable features of the Urals is a narrow, over 2000 km long belt in which high-pressure/low-temperature (HP/LT) metamorphic rocks outcrop along the western side of the Main Uralian suture (Sobolev et al., 1992). In the southwestern Urals, these HP/LT rocks outcrop within a narrow window (20 x 200 km), within the Uraltau dome. The dome structure is clearly attested at the surface by structural measurements of the metamorphic foliation (Matte et al., 1993; Matte, 1995) and at depth, by the URSEIS Vibroseis and explosion-source reflection profile (Fig. 1), in which the dome appears as an anticlinal stack (Berzin et al., 1996; Echtler et al., 1996; Knapp et al., 1996). On the section in Fig. 1A, mainly low-grade schists, probably of early Palaeozoic age (Suvanyak series), outcrop. It is hard to determine whether the antiformal bright reflectors visible between 5 and 8 s TWT in the Uraltau dome are due to the presence of competent Riphean beds (as is the case in the western foredeep) or, more likely, are due to a metamorphic banding within the micaschists and dense layers like eclogites. Such an alternation is visible in the high-pressure Maksuyuto complex, 150 km to the south in the Sakmara River. Here, the high-grade rocks are located along the easternmost margin of the Uraltau dome, beneath lower-grade Palaeozoic schists comparable to the Suvanyak series. The Maksuyuto complex consists of metasediments mainly of continental origin (phengite–glaucophane bearing micaschists, quartzites and meta-arkoses) and lenses of metabasalts, glaucophane–lawsonite-bearing eclogites, and enstatite-bearing metaperidotites. The whole complex has been metamorphosed at 550–600°C and 17–25 kbar (Dobretsov, 1991; Lennykh et al., 1995). This HP/LT metamorphism has been dated ca. 380 Ma by \(^{39}\text{Ar}/^{40}\text{Ar}\) on phengites of micaschists and eclogites (Matte et al., 1993). In the east, these rocks are separated from the low-grade Devonian sediments and volcanics of the Magnitogorsk arc by a complex east-dipping fault zone, the Main Uralian Fault (MUF), marked by various slices of ultramafic rocks (Fig. 1).

The MUF separates the continental part of the Urals in the west from the island arc complexes in the east, and is a major lithospheric boundary
at the scale of the whole Urals. The eastward dip of the MUF is clearly displayed by deep seismic profiling both in the central Urals (Sokolov in Zonenshain et al., 1990; Juhlin et al., 1995) and in the southern Urals (Knapp et al., 1996; Echtler et al., 1996) where it appears as a diffuse zone. This suture fault zone corresponds to the root of the oceanic klippe, like the Kraka massif, preserved to the west of the Uraltau dome in the Zilair synform (Fig. 1, section A). Various geological data suggest that the Main Uralian Fault worked as a major thrust during westward obduction of the oceanic lithosphere in Silurian–Devonian times (Matte, 1995; Echtler et al., 1997). On the other hand, a sharp metamorphic contrast between both sides of this oceanic suture as well as the ductile and brittle shear criteria indicating down-dip eastward movements, imply a normal sense of displacement along the MUF. The interplay
between thrusting and normal faulting as well as their chronology and succession are still poorly studied and remain unclear. The MUF separates the HP rocks from the low-grade fore-arc Devonian flysch of the Magnitogorsk volcanic arc. The Magnitogorsk volcanic arc consists of basalts, andesites and cherts well dated by conodonts. Beds are gently to tightly folded, locally with a steep cleavage, depending on their competence.

3. Comparison with Oman: low compressional regime of continental subduction

The structure of the southwestern Urals is very similar to that of the Upper Cretaceous orogen in Oman (Fig. 2) which, however, is simpler and better studied. The HP/LT rocks of Oman were metamorphosed under similar P/T conditions as in the Urals, that is, around 20 kbar at 500°C (Wills et al., 1991; Michard et al., 1994). These rocks have been exhumed within the Saih Hatat window, an analogue to the Uraltau dome. Both orogens have a comparable architecture. The HP/LT belts are bordered along their western sides by ophiolitic klippes, the Semail klippe in Oman and the Krak klippe in the Urals. On their eastern sides, the metamorphic belts are limited by major, very complex ductile faults. The Omanian fault has been studied in great detail (Michard et al., 1993; Searle et al., 1994; Mattauer and Ritz, 1996) and was shown to have operated first as a major thrust fault and then, during exhumation, as a normal fault with large (several tens of kilometres) normal-sense of displacement (Michard et al., 1994). The Main Uralian Fault seems to have the same nature (Matte and Chemenda, 1996).

The evolution of the Oman Mountains appears to correspond well to the model of low compressional regime of continental subduction depicted in Fig. 3. According to this model the continental subduction follows the subduction of the oceanic lithosphere (oceanic subduction) and during initial stages develops in the same way. This process changes when the continental crust fails upon reaching a depth of 150–200 km (Fig. 3a). The crustal slice subducted into the asthenosphere starts to rise rapidly under the buoyancy force, sliding over the mantle lithospheric layer (over weak and ductile lower crust). The rising slice intrudes the interplate zone (Fig. 3b). Removal (uplift) of the low-density crust from the mantle layer increases the pull force as this layer is slightly denser than the asthenosphere. An increased pull force facilitates the separation of the plates and the intrusion of the crust between them. This process is thus self-accelerating, with a maxim rate of crustal upward sliding reaching the usual rates of plate motion (i.e. from a few to several cm/yr). The rise of the crustal slice results in the formation of a major syn-obduction normal fault along the upper surface of the slice (Fig. 3b). Another consequence of this rising is an uplift and local extension of the frontal part of the overriding plate, which is then followed by separation of the tip of this plate (Fig. 3c). The previously subducted material is exhumed within the formed window (Fig. 3c) which corresponds to the Saih Hatat window in Oman. The removal of the

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**Fig. 2.** Cross-section trough Oman to the east of Muscat (from Chemenda et al., 1996): 1 = Arabian crust (a, upper strong and brittle layer, and b, lower weak and ductile layer); 2 = continental sedimentary cover (a, Permo-Mesozoic, and b, Proterozoic and Palaeozoic); 3 = oceanic lithosphere; 4 = oceanic sediments (Hawassina nappe); 5 = ductile fault; 6 = cleavage and folds; 7 = thrust (a) and normal (b) faults; 8 = eclogites exhumed from depth of near 60 km (ca. 20 kbar) (the arrows correspond to the stage of exhumation).
island-arc was built. The continental subduction in the Urals thus underwent a stage of arc–continent collision. Did this stage change conditions in the subsequent deep subduction and exhumation of the continental crust? To answer this question it is necessary to understand first what arc–continent collision means in terms of mechanics. We summarize below results of physical modelling of this process reported by Shemenda (1994) and Chemenda et al. (1997).

4. Arc–continent collision

Modelling shows that the presence of a volcanic arc (volcanics) on the overriding plate does not change the process of continental subduction shown in Fig. 3, unless this plate is sufficiently weakened. A weakening indeed occurs in the arc area due to a number of factors such as induced convection in the mantle, magmatic activity (presence of magma chambers and channels), and increasing water content which provides weak wet rheology of the overriding plate in the arc area. According to the physical modelling results, subduction of the continental margin progressively increases compression in the overriding plate. Compressive stress reaches the yield limit of this plate in the arc area (weak zone), causing its quasi-plastic shortening. Plastic deformation occurs through shearing along two opposite dipping systems of slip lines (Fig. 4b). The lithosphere then fails in either of these two directions, depending on two factors: the interplate friction stress, \( \tau_f \) (which is unknown in nature), and the average distance, \( L \), between the interplate zone and the volcanic arc (Fig. 4a). Failure along the fault dipping under the arc from its rear (to the left in Fig. 4) results in subduction reversal. If failure occurs along the fault dipping under the arc from the fore-arc basin, then the fore-arc block underthrusts the arc (Fig. 4c). This block can be subducted into the asthenosphere either completely (Fig. 4d), if it has a mantle density (or oceanic origin), or partly (Fig. 4e), if the density is lower (crustal/sedimentary composition). In the latter case, there is the possibility of a failure of the overriding plate at the opposite side of the arc, which would result again in subduction reversal.

Which of these options correspond to the Urals? It is generally assumed that the overriding plate in the Urals was oceanic, hence there remain only two

Fig. 3. Low compressional regime of continental subduction (from Chemenda et al., 1996): 1 = brittle, strong upper continental crust; 2 = ductile, weak lower crust; 3 = overriding plate.
Fig. 4. Possible modes of arc–continent collision (from Shemenda, 1994; Chemenda et al., 1997). Two possible scenarios are shown for lithospheric deformation: (a) to (d), and (a), (b), (c) and (e), which depend on the model parameters (see text for explanations).

options: subduction reversal or complete subduction of the fore-arc block into the mantle (Fig. 4d). We prefer the latter option. Indeed, the width of the fore-arc block (the distance between the accretionary prism and arc) in presently active oceanic subduction zones is 100–200 km. In the southern Urals it is clearly seen (Fig. 1) that the subduction complex (Zilair allochthon) is located just near the Magnitogorsk volcanic arc, which attests to disappearance of a large fore-arc space. Moreover, this complex underthrusts the arc, which fits well with the model in Fig. 4d (the accretionary prism is not shown in this model). The Kraka ophiolitic klippe, as well as mafic/ultramafic (Nurali) units rooted under the arc along the MUF (Fig. 1), could be what has been left from the subducted fore-arc block.

Deformation of the volcanic arc area, closure (underthrusting under the arc) of the fore-arc basin, and approaching the volcanic arc to the accretionary prism are currently going on in southern Taiwan (Suppe, 1981; Teng, 1990; Yu et al., 1995; Chemenda et al., 1997). This region is an example of active arc–continent collision where the Chinese (Asian) continental margin started (approximately 5 Ma) to subduct under the oceanic Philippine Sea Plate bearing the Luzon volcanic arc. The subduction of the fore-arc block seems thus to be a general phenomenon. Below, we combine the model for the
arc–continent collision (Fig. 4) with the low compressional regime model for deep subduction of the continental crust (Fig. 3) to develop an evolutionary model of obduction/exhumation in the southern Urals.

5. An evolutionary model for obduction in the southern Urals

Stage 1 of the model (Fig. 5a) corresponds to oceanic subduction) and the formation of the associated Magnitogorsk intraoceanic volcanic arc, probably in Silurian–Devonian time.

Stage 2 (Fig. 5b) starts with initiation of subduction of the European continental margin, which causes the following sequence of events: the increase in lithospheric compression, the failure of the overriding oceanic lithosphere in the arc area, and the underthrusting of the fore-arc block under the arc.

Stage 3 (Fig. 5c) corresponds to subduction into the mantle of the fore-arc block together with the underlying continental crust and sedimentary layer. The fragments of the sedimentary cover as well as the crustal and mantle slivers of this block are scraped off and accreted in front and under the arc. This process continues until the continental crust reaches a critical depth (more than 150 km). The subducted crust then fails at depths of several tens of kilometres giving start to the next stage: exhumation.

In stage 4 (Fig. 5d), the subducted crustal slice rapidly rises and intrudes the interplate zone between subducting and overriding plates. The slice slides over the mantle lithospheric layer which keeps subducting. This motion (sliding) first accelerates and then slows down, with the maximal rate reaching a few to several centimetres per year. The rising crust scrapes the sediments previously dragged into the interplate zone and pushes them up, producing uplift and extension of the overlying melange. This process in combination with erosion results in exhumation of previously subducted material within the Uraltau dome, which separates part of the accretionary complex including the ophiolitic klippes (Zilair, Kraka, Kimpersai) from the Magnitogorsk volcanic arc (stage 5, Fig. 5e). The eastern border of the dome coincides with the Main Uralian Fault. According to the model, this fault represents a complex suture zone, which at the stage of deep continental subduction was associated with a major thrust fault (zone), and at the stage of exhumation, with a major normal fault (zone) corresponding to the upper surface of the rising and deforming crustal/sedimentary body.

A removal (uplift) of the crust from the mantle layer of the subducted continental plate at the stage of exhumation (Fig. 5d) increases the pull force and results in rupture and sinking of the lithospheric mantle (Fig. 5e). This break-off removes the pull force which cause an increase in the horizontal compression of the lithosphere. Orogenesis drastically slows down in this part of the Urals, but continues to the east of the Magnitogorsk arc. It should be noted that in our model the breakage occurs within the continental lithospheric mantle and not in the transitional zone from the continental lithosphere to the oceanic lithosphere as supposed in the models of Sacks and Secor (1990) and Davies and von Blanckenburg (1995) for the slab break-off.

6. Conclusions

What is principally new in the proposed model is incorporation of the stage of arc–continent collision with a complete subduction into the mantle of the fore-arc block. This process was obtained in laboratory (physical modelling) and seems to fit well the geological situation in the southern Urals. There is no space for the fore-arc block on the geological profiles in Fig. 1. The arc–continent collision was ignored by all previous models for the exhumation of HP/LT rocks. The proposed mechanism, tested here in one particular region, may have a fundamental significance, providing a possible solution for the ‘low-temperature paradox’ of HP metamorphism. The exhumed high-pressure rocks are frequently (if not always) also low-temperature rocks, which means that they were preserved at relatively cold temperatures (ca. 700°C) at great depths (around 100 km), where temperature is normally greater than 1000°C. The temperature of the crust depends on the subduction rate and on such poorly constrained parameters as the exhumation rate and the thickness of the overriding plate in the subduction zone. One can ‘play’ with these parameters, trying to obtain the required low temperatures at the 100 km depth (near the failure location in Fig. 3c or Fig. 5c). However,
Fig. 5. Evolutionary model for obduction and exhumation of HP/LT rocks in the southern Urals: 1 = continental crust (a, upper strong, brittle layer, and b, lower weak, ductile layer); 2 = lower Palaeozoic and Riphean sediments; 3 = Silurian–Devonian flysch; 4 = mantle layer of the oceanic lithosphere; 5 = oceanic crust; 6 = Magnitogorsk volcanic arc; 7 = thrust (a) and normal (b) faults; 8 = marker corresponding to depth of several tens of kilometres (17–25 kbar) at the stage shown in (c).
there is another problem: a segment of the crustal slice, which is below the failure location, must also be cold enough to preserve its rigidity. The rigidity is needed to transmit the buoyancy force along the crustal slab and to push its upper parts to the surface. If the rigidity is low, then the subducted crust would ascend vertically (as a viscous slab) to the base of the overriding plate, without being able to intrude an interplate zone. The exhumation mechanism presented in Fig. 3 does not work under these conditions. Thus, the model of exhumation shown in Fig. 3 lacks some important elements which would provide for thermal screening of the subducted crust from the hot surrounding mantle. This element could be a subducted fore-arc block which conserves the continental crust, keeps it relatively cold, and hence rigid and strong (see Fig. 5).

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