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The 1.80–1.74-Ga gabbro–anorthosite–rapakivi Korosten Pluton in the Ukrainian Shield: a 3-D geophysical reconstruction of deep structure

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Abstract

The deep structure of the gabbro–anorthosite–rapakivi granite ("AMCG-type") Korosten Pluton (KP) in the northwestern Ukrainian Shield was studied by 3-D modelling of the gravity and magnetic fields together with previous seismic data. The KP occupies an area of ca. 12,500 km^2 and comprises several layered gabbro-anorthositic intrusions enveloped by large volumes of rapakivi-type granitoids. Between 1.80 and 1.74 Ga, the emplacement of mafic and associated granitoid melts took place in several pulses. The 3-D geophysical reconstruction included: (a) modelling of the density distribution in the crust using the observed Bouguer anomaly field constrained by seismic data on Moho depth, and (b) modelling of the magnetic anomaly field in order to outline rock domains of various magnetisation, size and shape in the upper and lower crust. The density modelling was referred to three depth levels of 0 to 5, 5 to 18, and 18 km to Moho, respectively. The 3-D reconstruction demonstrates close links between the subsurface geology of the KP and the structure of the lower crust. The existence of a non-magnetic body with anomalously high seismic velocity and density is documented. Most plausibly, it represents a gabbroic stock (a parent magma chamber) with a vertical extent of ca. 20 km, penetrating the entire lower crust. This stock has a half-cylindrical shape and a diameter of ca. 90 km. It appears to be connected with a crust–mantle transitional lens previously discovered by EUROBRIDGE seismic profiling. The position of the stock relative to the subsurface outlines of the KP is somewhat asymmetric. This may be due to a connection between the magmatism and sets of opposite-dipping faults initially developed during late Palaeoproterozoic collisional deformation in the Sarmatian crustal segment. Continuing movements and disturbances of the upper mantle and the lower crust during post-collisional tectonic events between 1.80 and 1.74 Ga may account for the long-lived, recurrent AMCG magmatism.

Keywords: Palaeoproterozoic; AMCG magmatism; Gravity; Magnetism; Deep-seismic sounding; Crust; Ukrainian Shield

1. Introduction

The anorthosite–mangerite–charnockite–(rapakivi) granite rock association (AMCG) is one of the most enigmatic products of magmatism, characteristic

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particularly of the Proterozoic. The relationships of AMCG intrusions with their country rocks are commonly "anorogenic", but there also exist suggestions of causal connection with large-scale lithospheric deformation (e.g. Korja and Heikkinen, 1995; Martignole, 1996; Duchesne et al., 1999; Corriveau and Morin, 2000; Martignole et al., 2000).

The western part of the East European Craton (EEC) has long been known as an area of recurrent AMCG magmatism (cf. Haapala and Rämö, 1992; Korja and Heikkinen, 1995; Åhäll et al., 2000; Puura and Flodén, 2000). In that region, the dense network of deep-seismic sounding (DSS) profiles shot during the last decade has shaped preconditions for a new understanding of the deep crustal structure beneath the AMCG plutons. Simultaneously, it has attracted new interest to the influence of these plutons on the geophysical characteristics of the crust and their relationships with crustal and upper-mantle deformation.

In 1997, the EUROBRIDGE seismic refraction/wide-angle reflection survey in southern Belarus and the northwestern Ukraine (Fig. 1) discovered a major

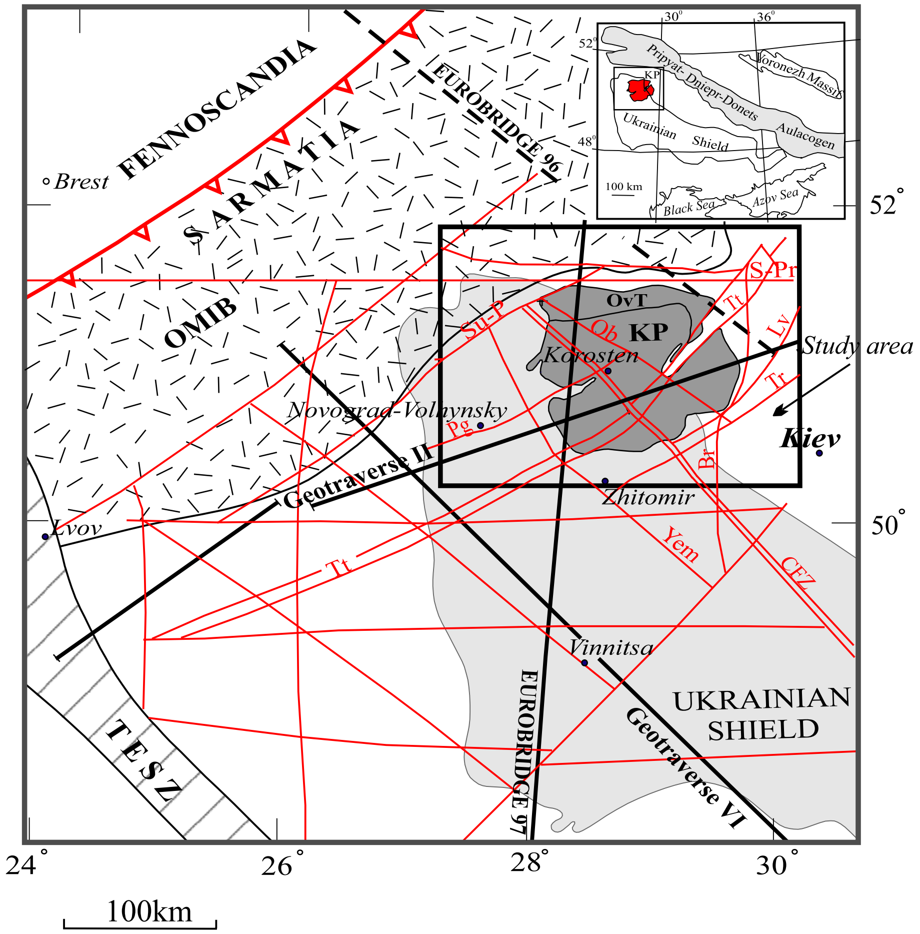


Fig. 1. Setting of the Korosten Pluton (KP) within the tectonic framework of northwestern Sarmatia. The positions of the major DSS profiles in that area are also indicated. In this map, the Ukrainian Shield is shown by light grey, the Korosten Pluton (KP) by dark grey shading. Some principal tectonic features are: OMIB—Osnitsk–Mikashevichi Igneous Belt; OvT—Ovruch Trough and TESZ—TransEuropean Suture Zone. The red lines and letters mark some of the major faults and fault zones in the study area. Here the letter symbols are: Br—Brusilov, CFZ—Central fault zone, Lv—Loev; Ob—Obikhodsky, Pg—Pugachevka; S-Pr—South-Pripyat, Su–P—Sushchany–Perga, Tt—Teterev, Tr—Troyanov, Yem—Yemilchino. The thick red dented line in the upper left indicates the boundary between the Fennoscandian and Sarmatian crustal segments. In the inset, the Korosten Pluton (KP) is shown in red and the Pripyat–Dniepr–Donets Aulacogen in grey.

southwards dipping mantle reflector (EUROBRIDGE Seismic Working Group, 2000) beneath Sarmatia. Sarmatia is one of the three major crustal segments of the EEC. Together with Fennoscandia and Volgo–Uralia, they define the structure of the entire craton, their Palaeoproterozoic collisional sutures having subsequently been activated by the formation of Meso- to Neoproterozoic aulacogens. In the Archaean and the early Palaeoproterozoic, however, the three crustal segments had entirely independent evolutions (e.g. Gorbatschev and Bogdanova, 1993; Bogdanova et al., 2001a,b).

The Fennoscandia–Sarmatia interface is marked by abrupt structural, lithological and metamorphic discontinuities in the crust and the upper mantle that were created by Palaeoproterozoic subduction–collision events between ca. 2.0 and 1.8 Ga (cf. Bogdanova et al., 1996; Taran and Bogdanova, 2001).

A spectacular feature apparently connected with these events outboard of Sarmatia was the formation of the 1.8–1.75-Ga giant Korosten AMCG massif in its northwestern part. Its short conventional denomination "the Korosten Pluton (KP)" will be used in the present paper even though it is, in fact, a complex of several separate mafic intrusions enveloped by a large volume of rapakivi-type granites. Being a potential site of ore deposits (e.g. Nechaev and Pastukhov, 2001), the KP has long been studied geophysically, petrologically, and geochemically (e.g. Shustova et al., 1978; Chekunov and Bolyubakh, 1979; Krasovsky, 1981; Sollogub, 1986; Zinchenko et al., 1990; Bukharev, 1992; Belevtsev et al., 1996). So far there is no consensus, however, in regard to the tectonic setting and the origin of the KP. Most of the named KP researchers, nevertheless, agree that the mafic intrusions are shallow, sheet-like bodies associated with steeply dipping gabbro-noritic feeder ring-dykes, and that the various rapakivi-type granitoids represent differentiation products of a single tholeiitic melt. Still, the precise composition of the parent magma and its source remain unclear, partly because the overall ratio of mafic rocks to granites in the KP is difficult to assess without knowing the variation with depth. Mitrokhin (2001) recently suggested a high-Al leucobasaltic composition.

Interpretations of the deep structure and mode of KP emplacement are also controversial due to sparse rock exposure and an absence of data on the relationships between the upper- and lower-crustal structures underneath the pluton. Some models suggest a vertical alternation of granitoid and mafic sheets in the upper and middle crust (e.g. Ilchenko and Bukharev, 2001), while others restrict the depth of the KP to between 3 and 6 km only (e.g. Zinchenko et al., 1990).

The present study attempts to close this knowledge gap by presenting 3-D density and magnetic models of the crust in the KP area. The new models also take into account previously available data in the EUROBRIDGE DSS (EUROBRIDGE Seismic Working Group, 2000) and Geotraverse II (Ilchenko and Bukharev, 2001) areas (Fig. 1) as well as other geological information.

2. Geological and petrological features of the Korosten Pluton

2.1. Country rocks

The Korosten Pluton (KP) was intruded into the Palaeoproterozoic Volhyn (also "Northwestern") Block of the Ukrainian Shield (Fig. 2). The repeatedly folded and migmatised Teterev supracrustal complex of 2.2–2.1 Ga age is the oldest rock unit in that region (e.g. Stepanyuk et al., 1998). Its gneisses are dominantly metasedimentary; metavolcanic lithologies are subordinate. They have been deformed and metamorphosed mostly in the lower-grade amphibolite facies, but pass locally into higher-grade amphibolite- and even granulite-facies rocks (e.g. Khvorova et al., 1982) associated with 2.06–2.02-Ga anatectic granitic magmatism (Claesson et al., 2000). The metamorphism and migmatisation were probably connected with the early stages of the development of the Osnitsk–Mikashevichi Igneous Belt (OMIB) in the northwestern part of the Volhyn Block (Fig. 1). The OMIB comprises large batholiths of mostly granodioritic to granitic rocks of 2.02 to 1.98 Ga age. Some gabbros and diorites are also present, while nearly coeval metavolcanics form small septa between the batholiths. The OMIB has many features in common with belts of magmatism at active continental margins, which suggests subduction of oceanic crust beneath the Sarmatian protocraton (cf. Bogdanova et al., 1996; Claesson et al., 2001).

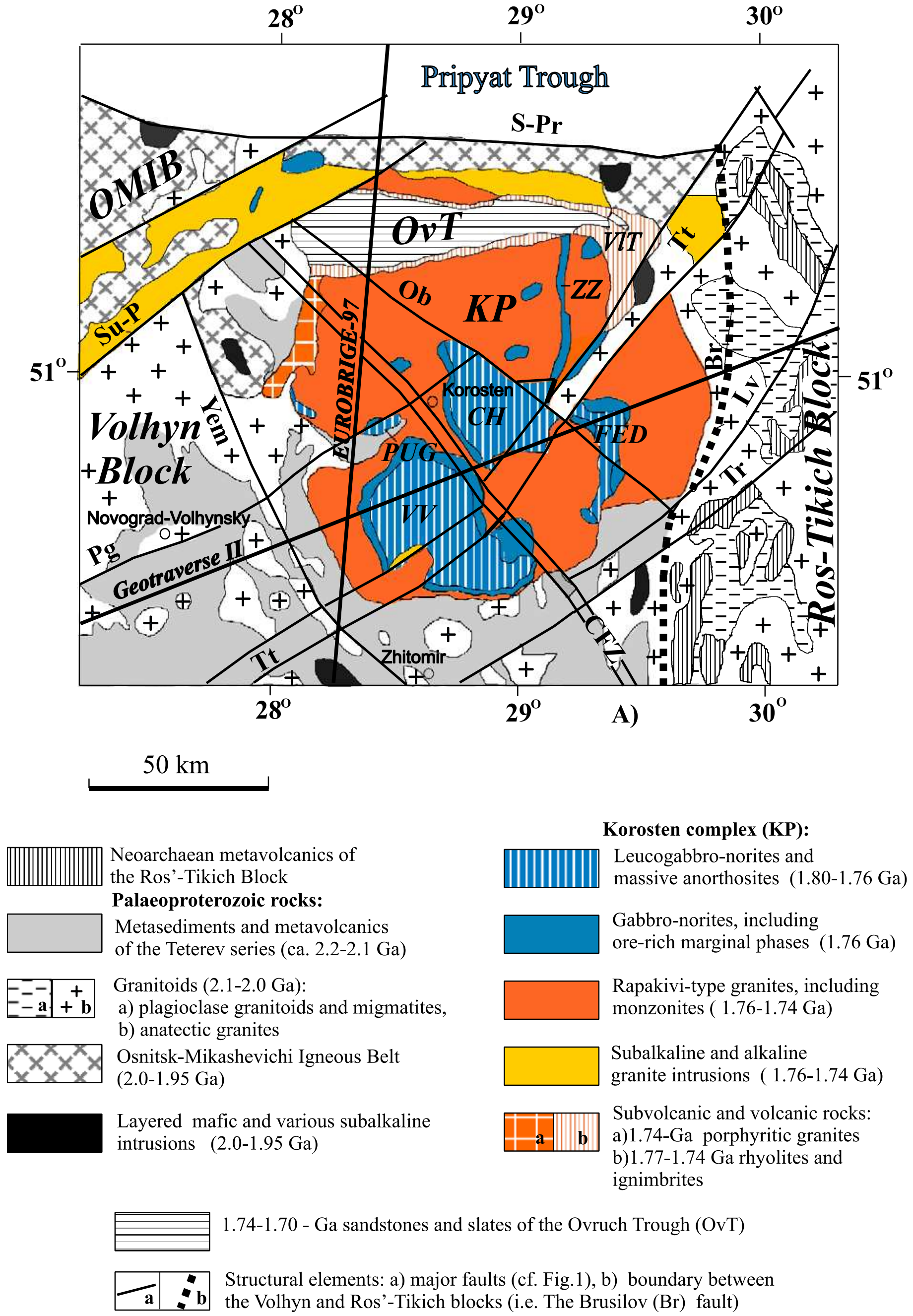


Fig. 2. Geological map of the Korosten Pluton (modified after Shcherbak and Volodin, 1984). The letter symbols marking the mafic intrusions of the Korosten Pluton are: CH—Chepovichi, FED—Fedorovka, PUG—Pugachevka, VV—Volodarsk–Volhynsky. Other features are: VIT—Vilchany Trough, ZZ—Zvizdal–Zalessie mafic dyke. The remaining letter symbols are explained in Fig. 1.

At the northern edge of the KP, the Ovruch Trough is partly filled with 1.75–1.73-Ga volcanics, genetically related to the plutonic rocks of the KP (Figs. 1 and 2).

The immediate contacts of the KP with its country rocks are usually not exposed, but parts of the contact zones can be observed. In the southwestern KP, there also exist roof pendants that have been strongly reworked and veined by aplites and pegmatites. Metasomatism occurred in 100- to 200-m-wide contact aureoles cutting across the tectonic grain of the country rocks. Around the mafic intrusions, zones of alternating fine-grained gabbros and hybridised gneisses occur. Numerous enclaves of country-rock gneisses are present in the anorthosites. The contact zones of the anorthosites with the rapakivi granites are mostly gradational but have been injected by rapakivi apophyses.

Well-developed contact metamorphism has affected the country rocks of the northern KP, where baked quartzites and hornfels–facies rocks occur in contact with 1.74-Ga porphyritic granites (Zinchenko et al., 1990). At the northeastern and southern KP contacts, the formation conditions of pyroxene hornfelses and skarns have been estimated as 800–900 °C at ca. 300 MPa (e.g. Khvorova et al., 1982), while zircons from an orthopyroxene hornfels rock in the northeast have yielded an age of ca. 1.74 Ga (Stepanyuk, personal communication).

2.2. Sets of faults

The KP area has been multiply faulted during various stages of its evolution (Figs. 1 and 2). The oldest sets of faults trend N–S and E–W and are mostly steep, often reverse (e.g. the Brusilov fault (Br in Fig. 1). They separate various Palaeoproterozoic domains. Zones of intense mylonitisation, high-grade reworking, and anatectic magmatism may associate with these faults.

The earliest faults are cut by NW- and NE-directed faults related to the development of the OMIB, along the northwestern margin of Sarmatia (Fig. 1). The younger faults control the distribution of numerous igneous intrusions of 2.1–1.95 Ga age. Commonly, the NE-trending faults are dextral shears dipping steeply to the northwest. These appear to be structurally linked with a major zone of faulting marking the edge of Sarmatia (cf. Bogdanova et al., 1996). Conspicuously, the rocks of the KP both intersect and follow the dense network of the ca. 2.0-Ga NW- and NE-trending faults. The largest mafic intrusions, for instance, are located in the immediate vicinity of the intersection of the Central (CFZ) and Teterev (Tt) zones of faulting (Figs. 1 and 2).

Even though the faults related to the Korosten igneous activity have themselves been masked by multiple magmatic events, the largest mafic plutons appear to be bounded by cone faults dipping inwards into the KP (e.g. Zinchenko et al., 1990).

2.3. The Korosten AMCG complex

The KP occupies a territory of ca. 12,000 km^2. At the present erosional level, granitoids prevail (82%), while mafic rocks comprise four large and several minor bodies. The large ones are the Volodarsk–Volhynsky (VV), Chepovichi (CH), Fedorovka (FED) and Pugachevka (PUG) intrusions (Fig. 2). Leucogabbros and gabbro–anorthosites predominate in these sub-plutons; anorthosites and mesocratic gabbroids are subordinate and ultramafic rocks rare. Monzonites (mangerites) mark the contact zones between the mafic- and the granitoid intrusions.

Coeval with the KP is a sequence of the 1.76–1.74-Ga sub-alkaline and alkaline granites, syenites and gabbros which follow the Sushchany–Perga tectonic zone 20 km to the north of the KP (Su–P in Fig. 1). Rhyolites, ignimbrites and trachybasalts comprising a relatively thin (tens to some hundreds of metres) volcanic flow at the base of the Ovruch Trough (OvT in Fig. 2) also appear to be an expression of late KP magmatism. Together with the Vilchany volcanics (VIT in Fig. 2), these rocks form an arcuate marginal belt in the northern KP area. Stocks and dykes of porphyritic granitoids cutting these supracrustals are present in its western marginal part.

Field relationships and geochronological data show that the KP intrusions were emplaced between 1.80 and 1.74 Ga, during several different phases of igneous activity (Amelin et al., 1994; Verkhogliad, 1995; Mitrokhin, 2001).

The earliest magmatic suite has ages of ca. 1.80–1.78 Ga (Verkhogliad, 1995; Dovbush and Skobelev, 2000). It is made up of anorthositic and leuconoritic cumulates that are more magnesium-rich than similar rocks of the later magmatic stages. High contents of B, and low TiO_2 (0.1–0.4%) and P_2O_5 (0. 05–0.07%)

are typical. The orthopyroxenes have high contents of Al_2O_3 (up to 4.9%), indicating crystallisation at relatively high pressures (Mitrokhin, 2001). It is important to note, however, that the rocks of this earliest magmatic suite are only found as enclaves/xenoliths in the rocks of the later igneous stages, suggesting that they were entrained from a deep-seated magma chamber. The xenoliths of the earliest rocks are most frequent in the Fedorovka intrusion, they also occur in the Pugachevka and in the northern marginal part of the Chepovichi intrusions, but have hitherto not been found in the Volodarsk–Volhynsky body. The largest single xenolithic block, the so-called "Ushomir massif" has an exposure area of ca. 15 km^2 in the southern marginal part of the Pugachevka intrusion. Its rocks have yielded the oldest U–Pb zircon and baddeleyite ages (1798 and 1794 Ma, respectively, Amelin et al., 1994) yet obtained from the KP.

The second magmatic phase at ca. 1770–1767 Ma is represented by grey, finely ovoidal amphibole–biotite–pyroxene–fayalite-bearing monzonites/mangerites and rapakivi-type granites occurring dominantly in the northeastern KP. The former are probably hybrid rocks since they are found in igneous contact zones between intruding rapakivi granites and overlying earlier gabbro–anorthosites (Bukharev, 1992). The oldest dated rocks of this phase are the Vilchany rhyolites in the north. These have yielded a U–Pb zircon age of 1770 ± 2 Ma (Verkhogliad, 1995) and have been erupted atop the eroded surface of country-rock gneisses and granites.

From ca. 1760–1758 Ma onwards, magmatic activity accelerated during a third phase, when a large amount of mafic rocks was produced. These form part of all horizontally layered intrusions but chiefly the Volodarsk–Volhynsky body. As during phase 1, gabbro–norites, leuconorites and anorthosites dominated the magmatism. The phase 3 suite is, however, more iron-rich (Fe# 45 to 62) and markedly layered, showing both cryptic and macroscopic layering.

The mineral compositions of the mafic rocks formed during phase 3 are more variable than those of similar rocks belonging to phase 1. Along with plagioclase and augite, orthopyroxene with low Al_2O_3 content (0.4–0.7%) is present. Several estimates of the PT-conditions of crystallisation of these rocks (cf. Belevtsev et al., 1996) have indicated 1000–1100 °C at 100–200 MPa (i.e. at depths of 4 to 7 km). Phase 3 was also characterised by low $p_{H_2}O$ and fO_2 (Belevtsev et al., 2001). Shallow conditions of magma crystallisation are additionally evidenced by the presence of sub-volcanic dykes of plagioclase porphyries of 1761 Ma age (Verkhogliad, 1995).

The third phase of mafic magmatism was completed by the emplacement of Fe–Ti–P rich sub-alkaline melts along the contacts of the earlier formed layered mafic bodies with the country rocks. The resultant fine-grained sub-alkaline gabbro–norites therefore often form near-vertical dykes. Along with plagioclase and pyroxenes, they contain olivine (Fe# 47 to 77), amphibole, and biotite. Apatite, ilmenite, magnetite and orthoclase are typical accessories, which makes these rocks different from similar gabbro–norites of the earlier intrusions (Mitrokhin, 2001). The richest deposits of ilmenite ore were formed during this phase of magmatism.

The subsequent granitoid magmatism, from 1752 Ma, produced voluminous intrusions of sub-alkaline biotite- and biotite-amphibole bearing rapakivi-like granites and leucogranites in the northern part of the KP (cf. Verkhogliad, 1995). This stage lasted until 1745–1737 Ma, when rhyolites and ignimbrites at the base of the Ovruch Trough were formed. Still later, minor gabbro to syenite intrusions and associated trachybasalts and dykes were emplaced.

Somewhat reducing conditions of crystallisation are a notable feature of all the KP igneous rocks. Minerals such as fayalite and ilmenite with haematite contents below 3% evidence oxygene fugacities in the field between the magnetite–wustite and magnetite–fayalite buffers (e. g. Belevtsev et al., 1996).

In regard to the composition of the parent magma, the Sm–Nd isotopic characteristics of the KP mafic rocks, with εNd ranging from − 0.2 to − 0.8 at 1750 Ma, apparently suggest involvement of crustal materials in the mafic melts (Dovbush and Skobelev, 2000) and contradict models involving the straightforward melting of a depleted upper mantle (e.g. Belevtsev et al., 1996, 2001). High-alumina mafic rocks, moved by collision into the lower crust and/or upper mantle, may represent a major remelted source of the KP magmas as well as the magmas of other AMCG suites (cf. Duchesne et al., 1999). Granitoids with εNd values around − 1.8 demonstrate even higher crustal contributions, contradicting a direct relationship with mafic melts (Dovbush and Skobelev, 2000) or a major admixture of such melts into melts derived from the crust.

In summary, the principal geological features of the Korosten Pluton (KP) are:

- The KP is a multiphase intrusive complex that took ca. 60 Myr to form.
- There is a predominance of granitoids at the present erosional level.
- There was a cyclic recurrence of initially mafic and subsequently granitoid magmatism at intervals of ca. 5 to 15 Myr.
- The siting of the AMCG magmatism was related to a system of fault zones originally formed at ca. 2 Ga. This system comprises the Central and Teterev sets of faults intersecting at the centre of the KP. The trends of these faults apparently also controlled the location of the various individual KP intrusions.
- The Fe/Mg ratios of the KP rocks, their Ti content and their alkalinities increased with time, which characterises both the mafic and the felsic lithologies.
- Reducing conditions of magma crystallisation and extensive fractional crystallisation caused high contents of ilmenite, apatite and fluorite in the late fractionates.
- Monzonitic (mangeritic) rocks were formed from hybrid melts at the contacts between the mafic intrusions and later rapakivi–granitic melts.
- With time, the levels of magma crystallisation became more shallow and igneous activity migrated to the north and northwest.

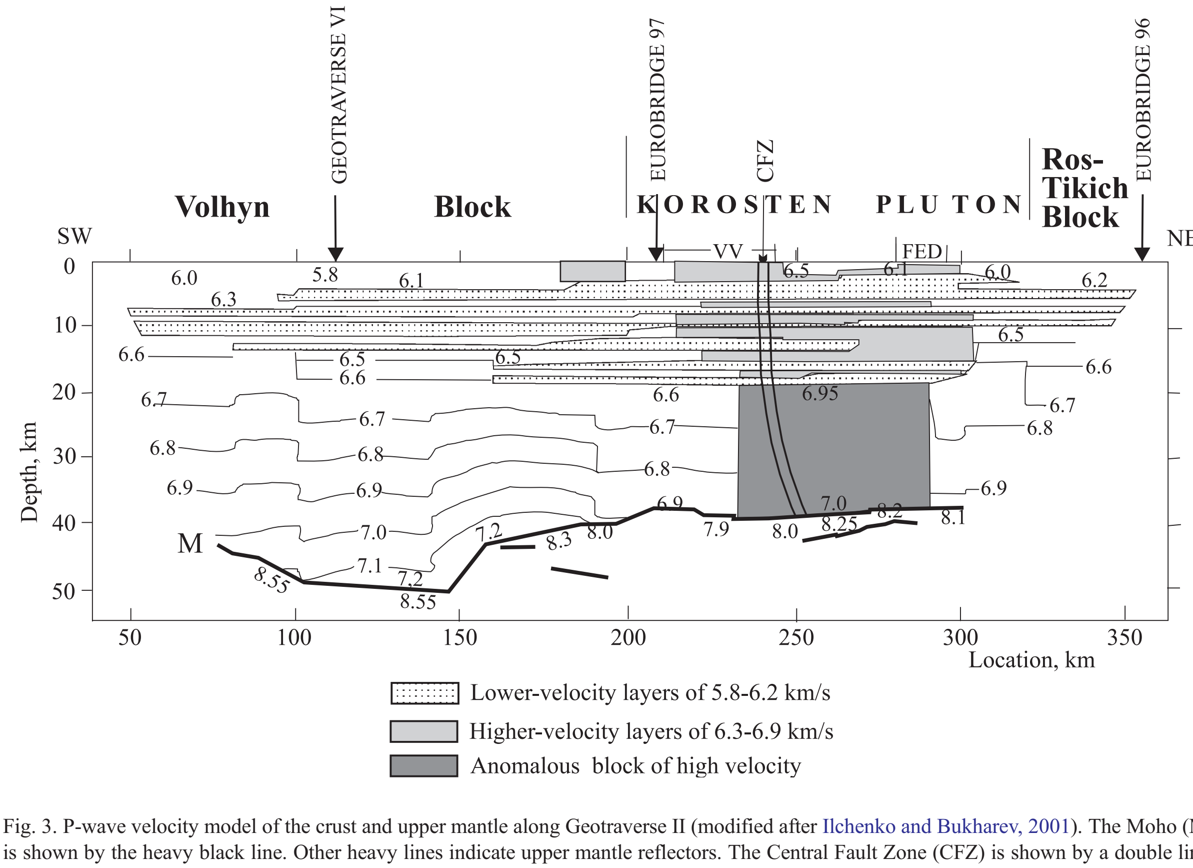


Fig. 3. P-wave velocity model of the crust and upper mantle along Geotraverse II (modified after Ilchenko and Bukharev, 2001). The Moho (M) is shown by the heavy black line. Other heavy lines indicate upper mantle reflectors. The Central Fault Zone (CFZ) is shown by a double line. The other letter symbols are as in Fig. 2.

- The crustal isotopic signatures of the mafic and granitoid rocks rule out simple partial melting of a depleted upper mantle. Collisional loading of high-Al mafic rocks (e.g. former oceanic and island-arc basalts) into the lower crust and/or upper mantle could have provided a relevant melt source for the KP magmas. Assimilation of crustal materials accounts for the more crustal isotopic characteristics of the granitoids.

3. Deep structure of the crust according to DSS data

The deep structure of the crust in the KP area has been revealed by DSS profile EUROBRIDGE'97 (EUROBRIDGE Seismic Working Group, 2000) extending across the western part of that area (Figs. 1 and 2) and by the Geotraverse II profile crossing its southern part (Ilchenko and Bukharev, 2001).

Beneath the KP, the Moho discontinuity rises to a depth of 38–39 km. This contrasts with depths between 42 and 52 km in the surrounding areas (Fig. 3). Similarly, all the other seismic boundaries in the KP crust also appear elevated (EUROBRIDGE Seismic Working Group, 2000). According to Geotraverse II (Fig. 3), the crust has a two-layered structure in which the upper layer represents an alternation of low- ($Vp = 5.8–6.2$ km/s) and high-velocity ($Vp = 6.3–6.9$ km/s) horizons. This seismic pattern has been traced across the entire Volhyn Block. The lower crustal layer, which occupies the depth range from ca. 18 km down to the Moho, is characterised by a highly differentiated velocity pattern that is somewhat different on the two sides of the Central Fault Zone. To the east of that fault, an anomalous block has a high Vp of 6.95 km/s at a depth of 18 km and 7.0 km/s at the Moho level. At the 18-km level, this is 0.3 km/s higher than the velocity in the neighbouring crust. Outside the anomalous block, Vp changes gradually with depth.

The most spectacular feature of the upper mantle in the KP area is a south-dipping reflector above which the Vp/Vs-ratios are lowered (EUROBRIDGE Seismic Working Group, 2000). That reflector may be the trace of a Palaeoproterozoic zone of subduction (cf. Bogdanova et al., 2001a,b). Similarly, an anomalous seismic zone in northwestern Sarmatia, which has been followed into the upper mantle by the Geotraverse-VI profiling, has been interpreted as the boundary between the Fennoscandia and Sarmatia crustal segments (Bogdanova et al., 1996).

4. 3-D density modelling

To reveal the deep structure and composition of the KP and adjacent areas, 3-D density modelling was employed. In particular, this allowed estimating: (a) the size, shape, and density of the seismically anomalous lower-crustal block mentioned above and (b) the density distribution in the upper, velocity-layered crust. The observed gravity data as well as the seismically derived Moho depths in the studied region were equally important in carrying out the modelling.

In regard to gravity, the map of observed Bouguer anomalies on the scale of 1:200,000 with a Bouguer correction of 2300 kg m^{-3} was used (cf. e.g. Kogan and McNutt, 1993).

The regional level of the observed gravity field changes from +15 mGal in the western part of the KP region to −15–20 mGal in its eastern part (Fig. 4a), indicating that the KP is subdivided into two different halves. The most pronounced zone of steep gravity gradient coincides with the Central Fault Zone. In contrast, no gradient zones mark the borders of the KP and the same regional gravity pattern continues uninterrupted beyond the area of the pluton. However, in the north, an intense minimum of −38 mGal outlines the Ovruch Trough.

Against that regional background, there exist local anomalies of various intensities and shapes that correspond to the subsurface structure of the KP. The different igneous intrusions (cf. Fig. 4) cause both highs (the ultramafic–mafic rocks of the marginal zones) and lows (the anorthosites and the rapakivi granites) in the observed field.

As far as the Moho is concerned, the previously published seismic depth data (Chekunov, 1992) were corrected on the basis of a new interpretation of Geotraverse II by Ilchenko and Bukharev (2001), and by reference to the results of the EUROBRIDGE'97 profiling (EUROBRIDGE Seismic Working Group, 2000). The accordingly assessed relief of the Moho discontinuity (Fig. 5) together with the Vp values of the

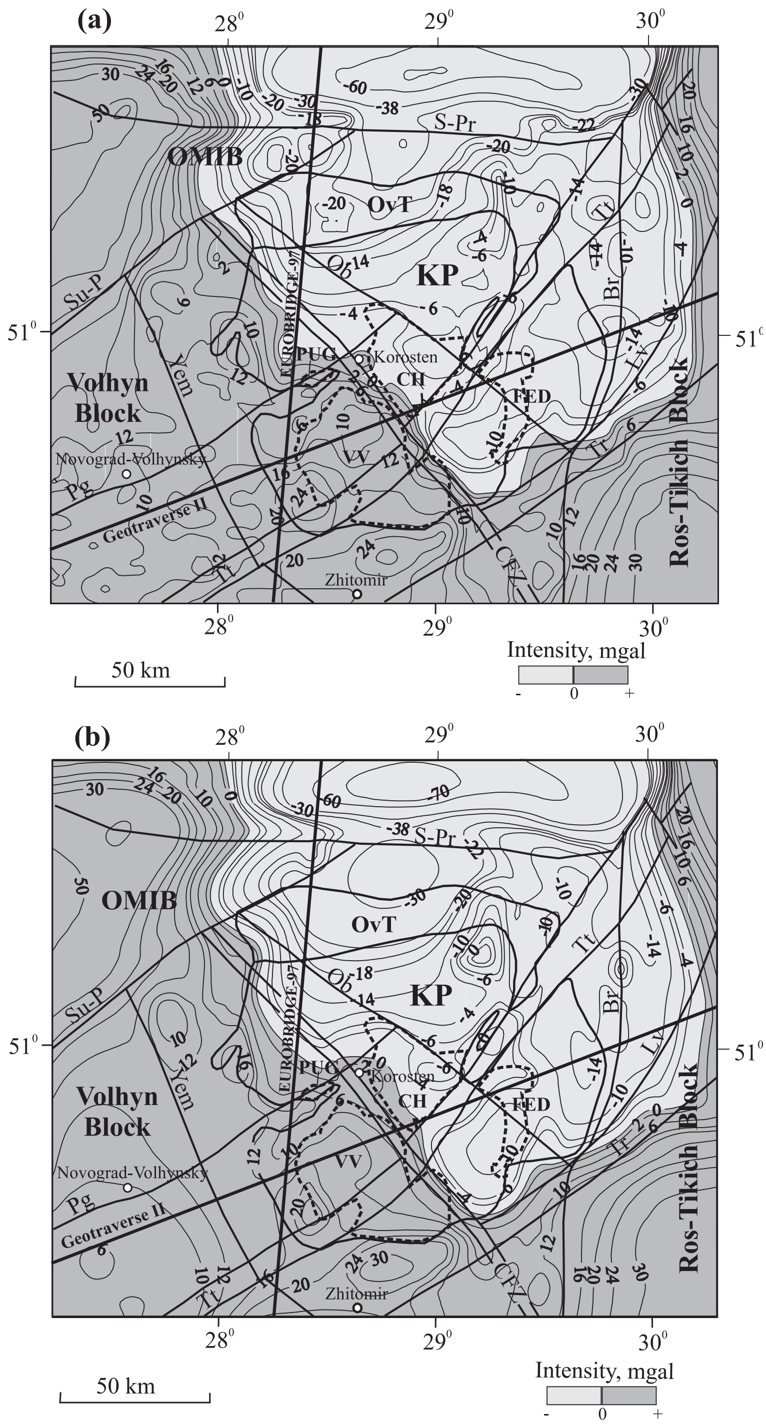


Fig. 4. Gravity anomalies (isolines in mGal) in the Korosten Pluton (KP) area, (a) observed and (b) calculated according to the 3-D crustal modelling. Heavy lines show faults and geological boundaries, dotted lines outline the KP mafic intrusions (cf. Fig. 2). The letter symbols are as in Fig. 2.

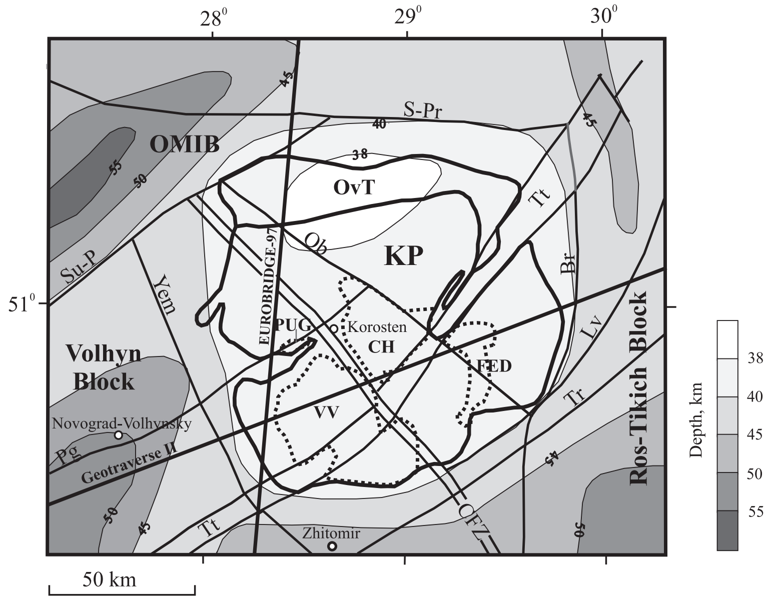


Fig. 5. Sketch map showing the relief of the Moho discontinuity in the KP area as compiled by DSS data. Heavy lines show faults and geological boundaries, dotted lines outline the KP mafic intrusions (cf. Fig. 2). The letter symbols are as in Figs. 1 and 2.

crust and the density properties of the subsurface rocks were then employed in the 3-D modelling.

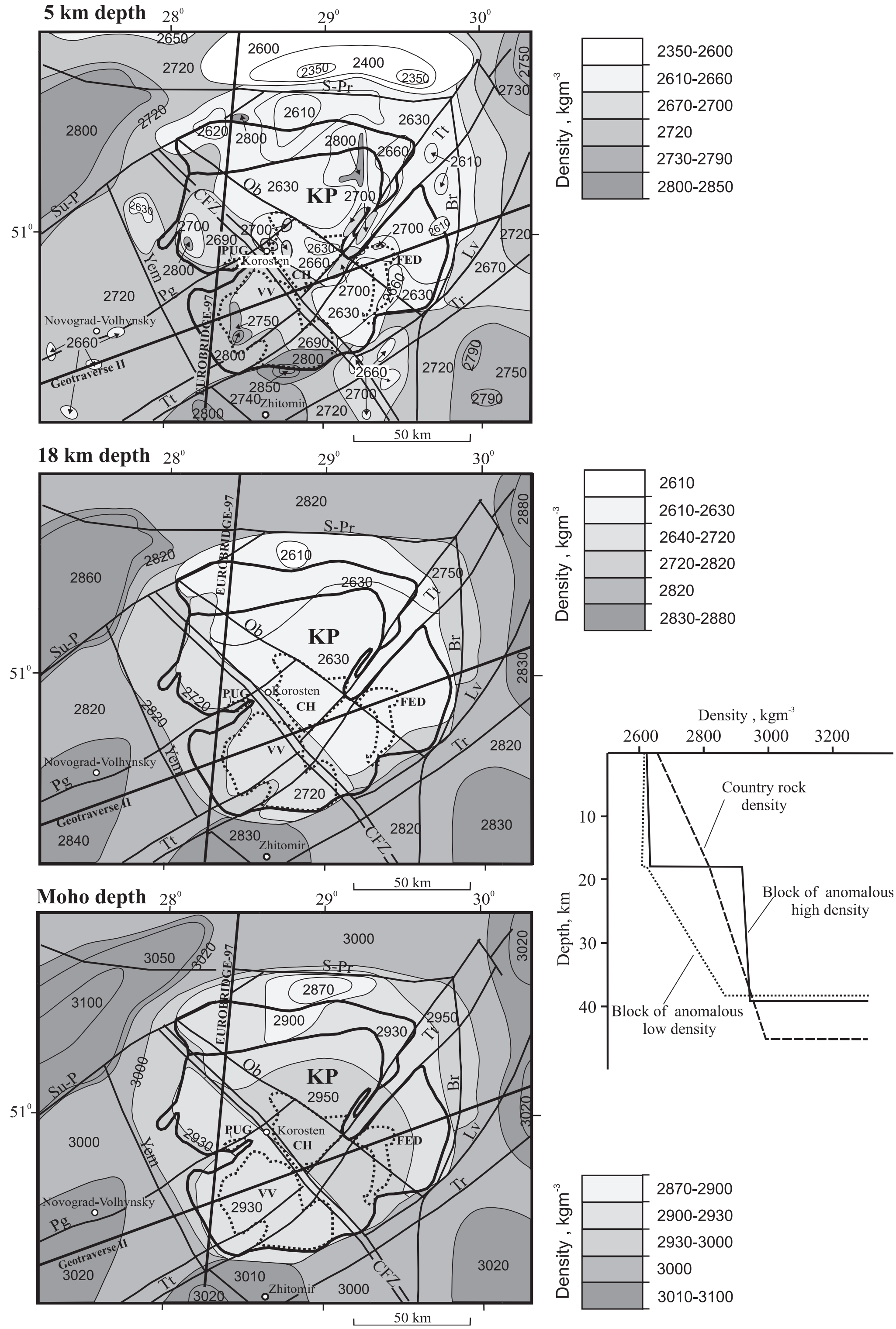
The calculations were made with the help of a computer programme using the input of the initial maps by scanning and solving the direct gravity problem for heterogeneous media. Most of the employed techniques were automatic and the presentation of the results is graphical (Starostenko et al., 1997; Starostenko and Legostaeva, 1998). The gravity effect of the crust was calculated on a 2.5- by 2.5-km grid that allowed estimating both the effects of the crust as a whole and that of local anomalies caused by subsurface sources. In the course of the modelling, the effects of density heterogeneities at distances up to 500 km from the KP were evaluated. The mean-square differences between the observed and the calculated gravity fields are of an order of ± 4 mGal (Fig. 4a and b).

Density parameterisation of the model layers was made on the basis of direct density data for rocks at the uppermost levels and on seismic velocity–density interdependence for the lower ones. Corrections of the density distribution within the calculated slices were performed in accordance with the statistically possible variations of the density values for any given Vp value. An upper mantle density of 3320 kg m^{-3} was adopted (cf. e.g. Buryanov et al., 1985).

The presented density model (Fig. 6) includes three depth slices of 0 to 5, 5 to 18, and 18 km to Moho depth. The gravity characteristics of these slices are as follows:

0–5 km. Beneath the exposure area of the KP, average density in the uppermost crustal layer varies between 2610 and 2630 kg m^{-3} to the east of the Central Fault Zone and between 2690 and 2700 kg m^{-3} to the west of it. This indicates a more granitic composition for the eastern KP. In the country rocks, density increases from 2650 kg m^{-3} at the surface to 2720 kg m^{-3} at the depth of 5 km.

Fig. 6. Density distribution in the crust at the 5- and 18-km depth levels, and at Moho depth. The profile shows density variations with depth in the KP area. Heavy lines show faults and general boundaries, dotted lines outline the KP mafic intrusions (cf. Fig. 2). The letter symbols are as in Figs. 1 and 2.


5 km depth
28°
29°
30°
51°
KP
S-Pr
Su-P
CFZ
Ob
Tt
Br
Lv
Tr
Yem
Pg
PUG
CH
VV
FED
Korosten
Novograd-Volhynsky
Zhitomir
Geotraverse II
EUROBRIDGE-97
50 km
Density , kgm^{-3}
2350-2600
2610-2660
2670-2700
2720
2730-2790
2800-2850
18 km depth
Density , kgm^{-3}
2610
2610-2630
2640-2720
2720-2820
2820
2830-2880
Moho depth
Density , kgm^{-3}
2870-2900
2900-2930
2930-3000
3000
3010-3100
Density , kgm^{-3}
2600
2800
3000
3200
Depth, km
10
20
30
40
Country rock density
Block of anomalous high density
Block of anomalous low density

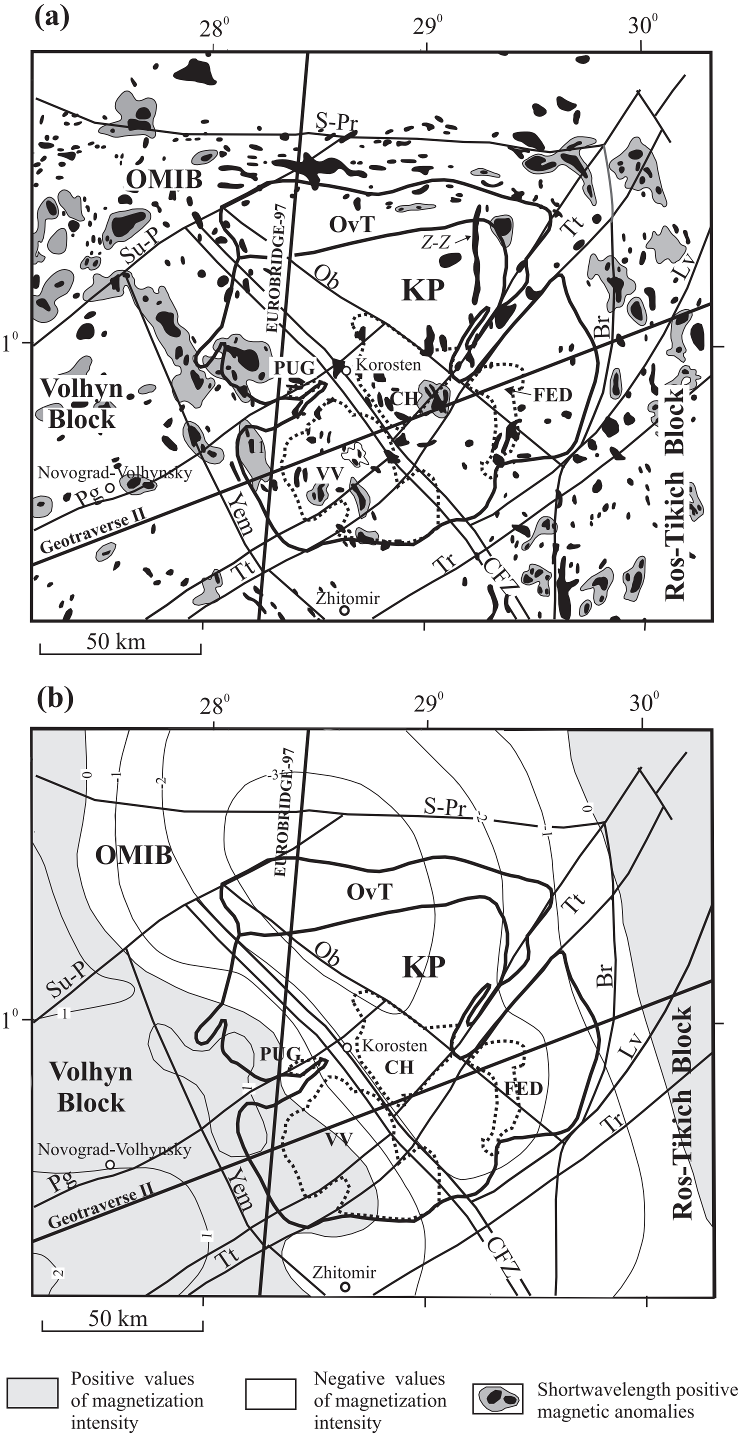


Fig. 7. Sketch map of the magnetic anomalies of the Korosten Pluton (KP) area: (a) local (short wavelength) magnetic anomalies; (b) regional (long wavelength) magnetic anomalies. The isolines are given in hundreds of nanoteslas (nT). ZZ—Zvizdal–Zalessie mafic dyke. Heavy lines show faults and geological boundaries, dotted lines outline the KP mafic intrusions (cf. Fig. 2). The letter symbols are as in Figs. 1 and 2.

5–18 km. At the 18-km level, the country rocks reach a density of 2820 kg m^{-3}, while the density distribution beneath the exposure area of the KP is similar to that within the uppermost crustal layer. The densities are 2720 kg m^{-3} to the west and 2630 kg m^{-3} to the east of the Central Fault Zone, a low density of 2610 kg m^{-3} being characteristic of the northern KP and adjacent areas. At the depth of 18 km, the density contour corresponding to the boundary of the KP extends farther towards the northeast and southwest than its equivalent within the uppermost (0–5 km) crustal level.

18 km-Moho. Against the background of a density increase from 2840 kg m^{-3} at the depth of 18 km to 3100 kg m^{-3} at the Moho, the eastern KP within this depth slice is characterised by a contrast in the density pattern (Fig. 6). In its central part, there is a large body of high density (2930–2950 kg m^{-3}), whereas in the north, a block of lower density (2620–2870 kg m^{-3}) is present. At the 18-km level, the high density body is manifested by a jump from 2630 to 2920 kg m^{-3} (Fig. 6). In the east, this body has the shape of a half-cylinder, while its western boundary trends subparallel to the Central Fault Zone. At the depth of 18 km, the high density body virtually coincides with the high velocity block defined by the DSS data (cf. Figs. 3 and 6). However, at Moho level, its western boundary (Fig. 7a) is displaced to the east relative to that of the high velocity block. Similar to the Central Fault Zone, it dips eastwards and corresponds to the projection of the Central Fault Zone onto the Moho (cf. Fig. 3). In contrast to the high velocity block, the high density block is thus rather asymmetrical in the E–W direction. A narrow continuation of the body occurs along the Central Fault Zone to the northwest.

In general, except at the southern border of the KP, a zone of transition up to 20 km wide is present between the crust of the KP and country rock crust at all depth levels.

5. 3-D magnetic modelling

To construct a magnetic model of the Earth's crust in the KP area, magnetic anomaly maps of the Ukrainian Shield on the scales of 1:200,000 and 1:500,000 were used (Krutikhovskaya, 1977). The reference field was approximated by the field of the first nine harmonics of the spherical harmonic decomposition. The precision of the obtained map of anomalies (cf. Fig. 7a,b) is ± 20 nT. In order to obtain regional anomalies, an upward continuation of the observed field to the altitude of 10 km on a grid of 2 by 2 km was computed. The mean square error of the mapped regional anomalies is estimated to be ± 25 nT.

The interpretation of the highest intensity local positive anomalies by solving the direct magnetic task and using a trail and error approach, preceded the 3-D magnetic modelling. Because of the limited sizes of these anomalies, a denser calculation grid of 1 by 1 km was used. Details of the 2-D and 3-D magnetic modelling techniques have been reported previously (e.g. Krutikhovskaya et al., 1982; Pashkevich et al., 1990; Orlyuk and Pashkevich, 1998).

The magnetic field of the KP comprises local, short wavelength (Fig. 7a) and regional, long wavelength (Fig. 7b) anomalies. The local positive anomalies schematically shown in Fig. 7a have sizes of some hundreds of metres to 30 km across and vary in intensity from some tens to a few thousands of nT. Their sources are, as a rule, mafic rocks of the KP, most of these being in the uppermost crust with only a few being more deeply seated. The shapes of local anomalies vary in accordance with the shapes of the mafic intrusions, linear, isometric and irregular configurations having been identified.

The regional anomalies have sizes of 100–150 km across and intensities between -300 and $+230$ nT. The sources of these anomalies are related to varying degrees of magnetisation in the middle and lower crust of the Ukrainian Shield (Krutikhovskaya et al., 1982). In the present study, these anomalies are considered to be produced by the heterogeneous layer of crust below the 18-km depth level.

The magnetic properties of the KP rocks range widely from non-magnetic or close to non-magnetic rapakivi-type granites and some gabbroids to highly magnetic gabbro-norites of the side intrusions in the Volodarsk–Volhynsky and Chepovichi bodies (Table 1). The gabbro–anorthosites and anorthosites of the Chepovichi and Fedorovka layered intrusions are weakly magnetised. Some of the weakly magnetised anorthosites of the Volodarsk–Volhynsky pluton show reverse magnetisation (Mikhailova et al., 1994). Analysis of the local anomalies indicates that the reversely magnetised rocks do not form markedly negative anomalies because of the low strength of the remanent magnetisation as well as the low intensities of the total (remanent and induced) magnetisation.

In general, there is a tendency for the magnetisation of the KP mafic intrusions to decrease from the southwest to the northeast. The northeastern KP is characterised by a negative regional magnetic field with local positive anomalies. The most intense linear anomaly is associated with the Zvizdal–Zalessie (ZZ) mafic dyke. Other linear anomalies follow dominantly EW- and NW-trending swarms of such dykes (Fig. 7a). Some of the local anomalies outline the Chepovichi and Fedorovka mafic intrusions. To the southwest of the Central Fault Zone, the regional magnetic field is positive, while the most intense local anomalies mark the arcuate margins of the Volodarsk–Volhynsky and Pugachevka ring-like intrusions. A separate belt of local anomalies follows the NW-trending Yemelchino (Yem) fault at the southwestern border of the KP. Both the regional and the local fields of the KP are thus asymmetric in relationship to the Central Fault Zone.

Table 1
Magnetic characteristics of the rocks from the Korosten Pluton (after Krutikhovskaya and Pashkevich, 1976; Krutikhovskaya et al., 1982; Mikhailova et al., 1994)

Rock types (number of samples)	Remanent magnetization I_n, A/m (mean values)	Magnetic susceptibility χ, 10^{-5}, SI (mean values)
Korosten Pluton		
Rapakivi and rapakivi-type granites (1914)	0.01	< 30
Volodarsk–Volhynsky mafic intrusion		
Anorthosite (127)	0.365	378
Gabbro–anorthosite (150)	0.458	630
Gabbro (115)	0.197	348
Gabbro (57)	0.647	3149
Monzonite (8)	0.162	203
Chepovichi mafic intrusion		
Gabbro–anorthosite (56)	0.316	214
Gabbro–anorthosite (34)	1.152	1312
Olivine gabbro (56)	1.952	1352
Ore gabbro (46)	24.700	5885
Diabase (8)	0.293	2204
Diabase (7)	0.005	66
Diabase (8)	0.381	414
Monzonite (3)	0.019	235
Fedorovka mafic intrusion		
Gabbro–anorthosite (31)	0.171	144
Gabbro (33)	0.314	387
Zvizdal–Zalessie mafic dyke		
Diabase (38)	0.608	307
Diabase (8)	4.810	1408

A 3-D magnetic model of the crust beneath the KP was produced using recent interpretations of DSS and heat flow data (Ilchenko and Bukharev, 2001; EUROBRIDGE Seismic Working Group, 2000; Kutas and Zui, 1999). In accordance with the previously developed interpretation techniques (Krutikhovskaya et al., 1982; Pashkevich et al., 1990; Orlyuk and Pashkevich, 1998), the experimental results in regard to magnetic rock properties were employed to calculate the depths of the lower borders of the subsurface magnetic sources. To estimate the positions of these borders of the deep-seated magnetic blocks, data describing the range of Curie temperatures between 420 and 590 °C (Mikhailova et al., 1994) were introduced. The magnetisation of the deep-seated sources was estimated from petrophysical data on lower crustal xenoliths and high-grade/high-pressure rocks (Pechersky et al., 1994).

For each deep-seated crustal block, intervals of the magnetisation intensity were obtained by several iterations. The magnetic anomalies caused by these blocks were calculated on a 5- by 5-km grid. The effects of magnetic heterogeneities in country rocks at distances of up to 100 km from the KP area were also estimated. The differences in the intensities of the regional and calculated fields are in the range of ± 20–30 nT, which corresponds to the errors of the regional anomaly calculations (cf. above).

5.1. The upper crust

Only the most intense and isolated positive local anomalies were interpreted prior to the 3-D modelling.

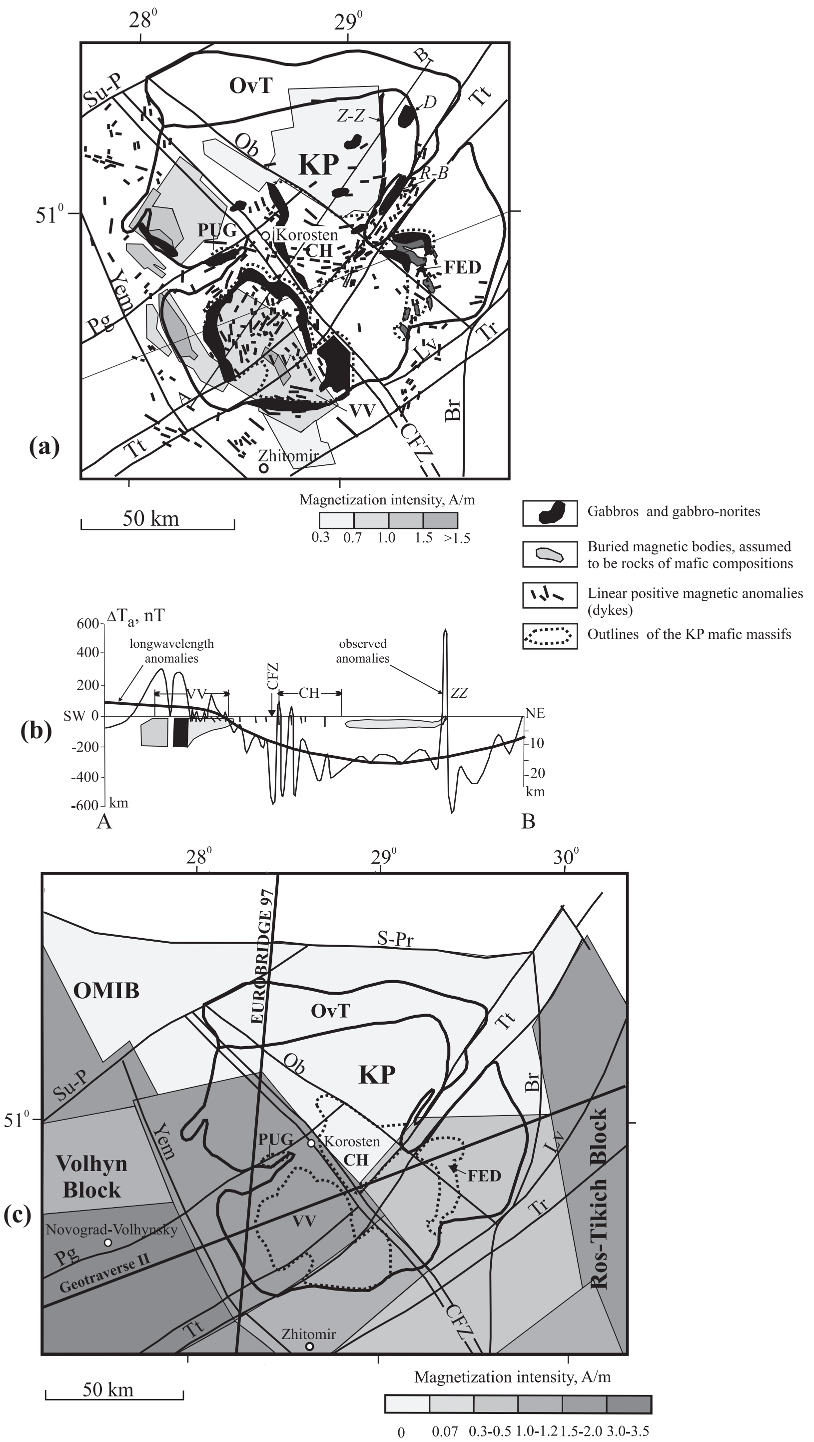


Fig. 8. (a) 3-D magnetic model of the upper crust beneath of the Korosten Pluton (KP); (b) cross-section of the upper crust along the A–B line of sub-figure (a); (c) sketch map of the deep-seated magnetic blocks below the 18-km depth level. Heavy lines show faults and general boundaries, dotted lines outline the KP mafic intrusions (cf. Fig. 2). The letter symbols are as in Figs. 1 and 2.

The sources of these anomalies have depths ranging from some hundreds of metres to 10 km, the errors of these estimations being ca. 20–30%. The largest depths are characteristic of steeply dipping bodies in the marginal parts of the Volodarsk–Volhynsky and Chepovichi mafic intrusions (Fig. 8a). Several sub-horizontal magnetic bodies are up to 3 km thick, their upper edges occurring at depths ranging between 100 m and 4 km. These flat-lying bodies may be composed of gabbro–anorthosites with magnetisation intensities of 0.7 to 1.0 A/m and occur within the Volodarsk–Volhynsky and Pugachevka mafic intrusions (Fig. 8b). A sheet-type body of low magnetisation appears to continue the Chepovichi intrusion towards the north (Fig. 8a). Linear dyke-type anomalies are widespread within the Volodarsk–Volhynsky intrusion; they follow in part the arc-shaped margins of that intrusion.

5.2. The lower crust

The lower crust in the KP area is variously magnetised (Fig. 8c). Four distinct blocks that are related spatially to the NW–NE system of faults characterising the region can be recognised. All these lower crustal blocks continue beyond the limits of the KP. A virtually non-magnetic block occupies the northern part of the KP area between the Teterev and Central fault zones. These faults also delimit the weakly magnetised (0.07 A/m) block in the east. To the west of the Central Fault Zone, the lower crust is somewhat more magnetic (1–2 A/m). However, the lower crust in the country-rock areas is, in general, more magnetised than the lower crust of the KP proper.

An important result of the present modelling is that the intersection of the four lower-crustal magnetic blocks coincides with the mid-point of the KP area, where mafic magmatism has been best expressed. However, each of the major KP mafic intrusions is associated with its own specific type of magnetic block. Thus, the Chepovichi intrusion is within a non-magnetised crustal block, the Fedorovka intrusion in a weakly magnetised one, while the Volodarsk–Volhynsky and Pugachevka igneous bodies coincide with the most strongly magnetic blocks among the KP intrusions.

6. The integrated 3-D geophysical model

Integrating the gravity, seismic, and magnetic reconstructions of the deep structure of the crust (Fig. 9) with information on the geology and the shallow subsurface structure allows the following characteristics and regularities to be established:

- The crust of the KP is marked by an elevated Moho and similar elevation of all the other crustal layers. In comparison with the surrounding country-rock areas, the crust of the KP is generally less dense and less magnetic. Its structure and composition are pronouncedly asymmetric relative to the Central Fault Zone, which divides the KP into unequal northeastern and southwestern parts.
- The upper crust of the northeastern KP is less dense than that in the southwest and contains a few local magnetic bodies. The latter, in contrast, features large highly magnetised rock units, some of these sheet-like, and others steep and extending to great depths. The thickest of these bodies related to the Volodarsk–Volhynsky intrusion reaches depths between 5 and 10 km. The others are not thicker than 2 to 3 km. Beneath the rapakivi granites that formed during igneous phase 4, the 3-D reconstruction of the upper crust indicates a continuation of the Pugachevka mafic rocks nearly 25 km towards the north–west.
- The lower crust, extending from the 18-km depth level to the Moho differs significantly across the Central Fault Zone. In the southwestern KP, the crust is intensely magnetised, and its density and Vp velocity change gradually with depth. Beneath the northeastern KP, in contrast, the magnetisation of the lower crust is weak whereas density varies substantially. According to the 3-D density model and seismic data, a very prominent feature is the presence of a homogeneous, seismically transparent, high velocity and high density body of half-cylindrical asymmetric shape and a size of ca. 90 km across.
- A low density crustal block in the northern KP indicates that the late-phase rapakivi granitoids and the felsic volcanics dominating the surface in the Ovruch area belong together with intrusions extending down to 30–35 km.

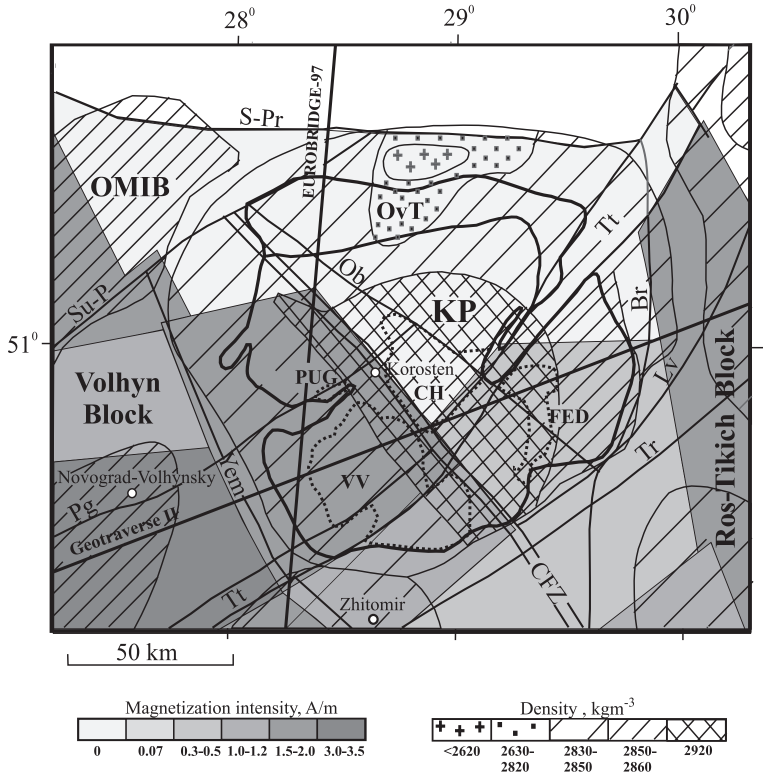


Fig. 9. Density and magnetic heterogeneities below the 18-km depth level in the crust beneath the Korosten Pluton (KP). Heavy lines show faults and geological boundaries, the dotted lines outline the KP mafic intrusions (cf. Fig. 2). The letter symbols are as in Figs. 1 and 2.

- The intersection of the Central Fault Zone, the Teterev faults, and the related magnetic blocks in the lower crust, coincides with the vertical axis of the high velocity/high density body described above. It appears to be connected with a lens of high velocity lower crust just above the Moho (EUROBRIDGE Seismic Working Group, 2000), which may have a composition transitional between those of the lower crust and the upper mantle.

7. Discussion

7.1. Relationships of the KP sub-surface geology with the deep structure and composition of the crust

The KP comprises several layered mafic intrusions surrounded by voluminous granitoids. The 3-D geophysical model of the crust demonstrates that these mafic intrusions are relatively shallow, only extending to depths between 2 and 7 km. Somewhat deeper are the flanking high-angle intrusions which reach down to ca. 10 km.

The granitic intrusions formed during several stages of igneous activity and have affected the entire upper crust of the KP. It is imaged as having a highly layered seismic pattern (Fig. 3), decreased crustal densities, and a magnetisation weaker than that of the surrounding country-rock complexes. The degree of "granitic reworking" was different in the northeastern and the southwestern KP. In the northeast, the upper crust contains ca. 50% granitoid rocks, while in the southwest, they amount to ca. 20%. This results in average upper crustal densities of 2630 and 2690 kg m^{-3}, respectively (Fig. 6).

The 3-D reconstruction demonstrates a close connection between the upper and lower crustal structures of the KP. The anomalous high velocity/high density non-magnetic half-cylindrical body in the lower crust (Figs. 3 and 9) can be interpreted as a mafic stock with a vertical extent of ca. 20 km, i.e. penetrating the entire lower crust. An overall gabbroic composition for this body is inferred from Vp values of 6.95–7.0 km/s and densities of 2920–2950 kg m^{-3}. The position of this stock beneath the northeastern KP and its alignment with the Central Fault Zone invite its interpretation in terms of a major supplying conduit for mafic melts and associated asymmetric granitic emplacement into the upper crust (Fig. 10).

The rather deep density low of 2610 kg m^{-3} in the northern part of the KP area (Fig. 6) is probably due to late granitic events structurally connected with the development of the Mesoproterosoic Ovruch Trough.

The Volodarsk–Volhynsky and Pugachevka mafic intrusions in the southwestern KP are underlain by a lower crust that resembles the country-rock crust of

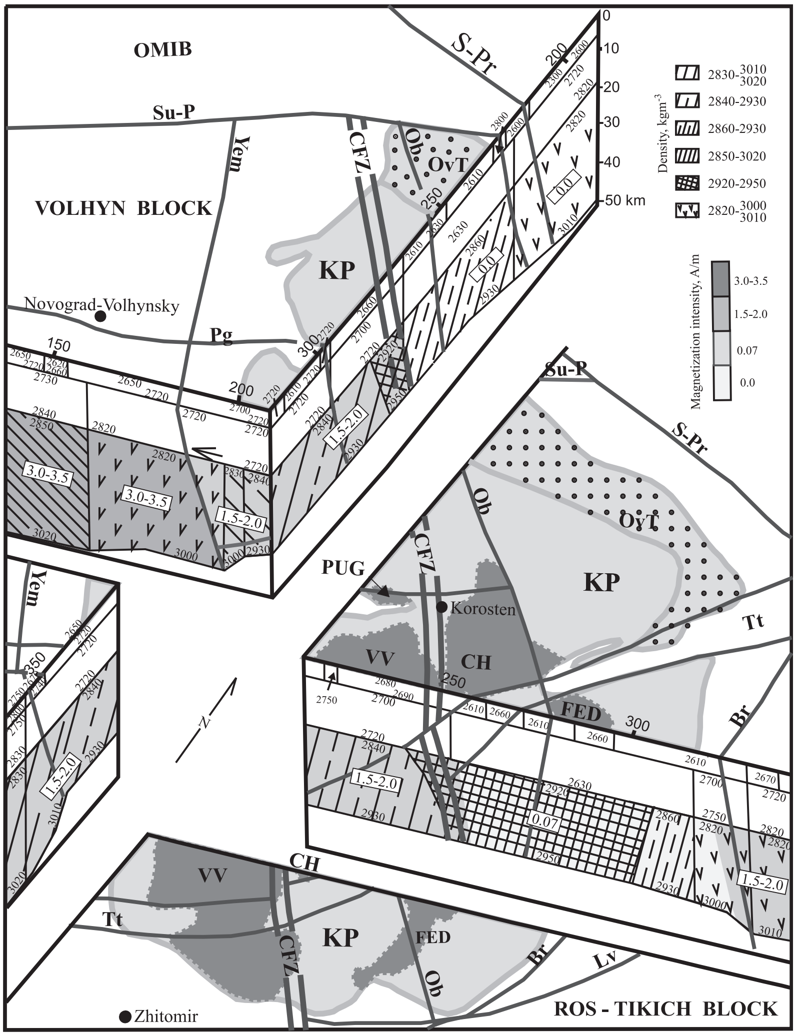


Fig. 10. 3-D sketch block diagram of the KP area showing the siting of deep-seated density and magnetic heterogeneities in the crust. The KP mafic intrusions are shown by dark grey the other KP rocks by light grey shading. The large digits along indicate distances in km. The letter symbols are as in Figs. 1 and 2.

the Volhyn Block by featuring gradually varying seismic and density patterns (Figs. 3 and 6), and a high magnetisation for the lower crust (Fig. 8c). As suggested by the calculated physical properties (Vp 6.6–6.9 km/s, density 2.840–2.930 kg m^{-3}, magnetisation 2 A/m; Krutikhovskaya et al., 1982; Pechersky et al., 1994), mafic granulites prevail in the lower crust of the southwestern KP, in the area to the west of the Central Fault Zone.

7.2. Role of the 2.0–1.8 Ga fault system and particularly the Central and Teterev Fault Zones in the emplacement of the KP mafic melts

The distribution of the major mafic intrusions around the intersection of the Central and Teterev deep fault sets strongly suggests that the emplacement of the mafic magmas into the upper crust was controlled or at least influenced by the system of NW- and NE-trending fault zones. These complementary, cross-cutting sets of subparallel faults record the long tectonic evolution of the Sarmatian continental margin between 2.0 and 1.8 Ga, when it faced the oceanic crust that was subsequently consumed during docking with Fennoscandia (e.g. Taran and Bogdanova, 2001). That evolution was marked by subduction of oceanic crust beneath the Sarmatian protocontinent, the associated development of the OMIB continental-margin igneous belt and, subsequently, the collision of rigid Sarmatia with Palaeoproterozoic juvenile arc terranes. A collisional interaction of the Sarmatian continent with another continent (for instance, Fennoscandia) at 1.82–1.80 Ga is proposed as a possible explanation of the substantial thickening of Sarmatian crust preceding the Korosten magmatism (Bogdanova, 2002).

The continuation of the NE- and NW-trending fault zones down into the middle and lower crust demonstrate that their intersection also continues downwards until truncated by the Moho (Figs. 10 and 11). This situation recalls some results of the experimental modelling of convergent boundary tectonics, in which subductional–collisional events lead to the formation of doubly vergent shear zones above the "singularity point" from which the subducting slab dips into the mantle (e.g. Beaumont et al., 1996). In the case of the northwestern margin of Sarmatia, the accretion of juvenile Palaeoproterozoic crust must certainly have resulted in the development of both precollisional (before 1.8 Ga) and collisional crustal tectonic fabrics. Thus, the strong and repeated deformation of the crust with detachments at the Moho boundary and probably also in the middle crust, as indicated by sharp seismic velocity gradients and discontinuities (EUROBRIDGE Seismic Working Group, 1999), may have played a role in controlling the late-to post-collisional AMCG magmatism and the resultant formation of the Korosten Pluton.

7.3. Influence of tectonics and country-rock compositions on the variable magnetisation patterns in the lower crust beneath the KP

The collisional tectonics considered above also appears to have been one of the major controls of the variable degrees of magnetisation in the lower crust of the KP area (Fig. 8c). Highly and moderately magnetised as well as virtually non-magnetised blocks are juxtaposed along the Central, the Teterev, and other major fault zones. The block mosaics in the lower crust beneath the KP may thus be a result of the tectonic juxtaposition of wedges of Palaeoproterozoic and Archaean crust. This tectonic style was particularly active along the northwestern margin of Sarmatia. The reflection seismic profile crossing that margin and described by Juhlin et al. (1996) clearly demonstrates the wedged structure of the crust in the area. The highly magnetised blocks to the southwest of the Central Fault Zone may consist of mafic metavolcanics of the Palaeoproterozoic oceanic crust. Krutikhovskaya et al. (1982) have shown that the high-grade metamorphic rocks, particularly the metavolcanics in the western Ukrainian Shield have the highest degree of magnetisation among all the rocks of the region. The less magnetised blocks are probably slices of metasediments, granitoids, and migmatites of both Archaean and Palaeoproterozoic ages. It is notable, however, that the gravity asymmetry in the KP area (Figs. 4 and 6) is not markedly related to lower crustal blocks defined by the magnetic anomalies but is, instead, controlled by upper and middle crustal sources. These conditions could be due to the voluminous granitoid magmatism that affected profoundly the upper crust in the eastern part of the KP.

8. Concluding remarks on the origin of the KP

The 3-D geophysical reconstruction of the deep structure of the KP establishes new constraints for its origin:

- The thick gabbroic body in the lower crust related to a crust–mantle transitional lens appears to represent the parent magma chamber which periodically supplied its melts to the KP (Fig. 11). The asymmetrical position of this thick, half-cylindrical stock relative to the subsurface outlines of the KP may be due to the close connection between the magmatism and the fault sets developed during the late Palaeoproterozoic collisional and post-collisional deformations of the Sarmatian crust. The asymmetry could have been caused by the attendant wedge-mosaic patterns in the lower crust and upper mantle, where subsequent melting of (meta)basalts (cf. Duchesne et al., 1999) producing the parental melts of the KP occurred to the east of the Central Fault Zone. This fault zone controlled for the most part the northeastern dips of the KP rock bodies (Figs. 10 and 11).
- The sharp decrease of density in the upper crust just above the gabbroic stock is still enigmatic. It may indicate extensive mixing/mingling of massive anorthosites and rapakivi granitoids with thin sills and dykes of denser mangerites. Apart from the Korosten granitic melts proper, remelting of the Palaeoproterozoic supracrustal rocks that dominate the upper crust in the Volhyn Block around the KP could account for the multiple seismic layering suggested by Geotraverse II (Fig. 3).
- It appears likely that the complex AMCG magmatism that lasted ca. 60 My required some rather specific tectonic conditions to provide repeated magma ascents and emplacements into the upper crust. Post-collisional tectonics in immediate con-

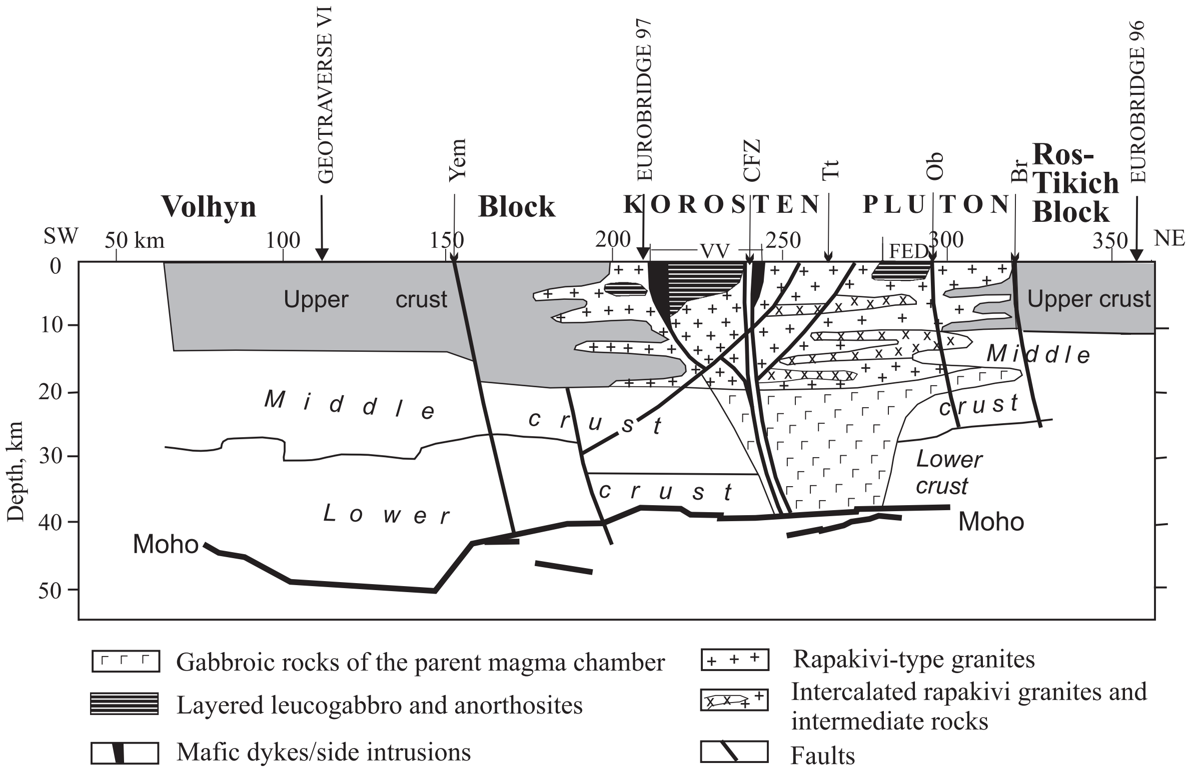


Fig. 11. Tentative geological interpretation of the deep structure of the Korosten Pluton and the surrounding area. This cross-section follows Geotraverse II. The letter symbols are as in Figs. 1 and 2.

tinuation of collisional movements under conditions of gravitational instability have recently been discussed as one of the most important settings of post-collisional magmatism (e.g. Martignole, 1996; Liégeois et al., 1998; Duchesne et al., 1999). It would appear that the AMCG magmatism in the KP was no exception in that regard.

- Continuing movements and disturbances of the upper mantle and the lower crust as recorded by the subparallel patterns of the NW- and NE-trending fault zones may also be an explanation of the specifics of KP magmatism. At least two major periods of mafic-to granitic magmatism are now recognised as well as an apparent displacement of the magmatic activity to the north with time. Duchesne et al. (1999) proposed a model for the formation of massive anorthosites in which melting of lower crustal mafic slices ("crustal tongues"), tectonically entrained into the upper mantle along major crustal boundaries, results in AMCG magmatism. Many of the petrological and geophysical characteristics of the Korosten Pluton agree with this idea.

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