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Distribution of Precambrian iron and gold deposits on the southwestern East European Platform reflected in underlying transcrustal structure and current river systems

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Abstract

The East European Platform is underlain by Archaean and Proterozoic complexes of the East European Craton. In the southwest these are locally exposed in the Ukrainian Shield and the Voronezh Massif on either side of the ca. 2000 km long ESE-striking late Palaeozoic Pripyat–Dniepr–Donets rift. Evaluation with Landsat imagery of 1 : 1,000,000 scale published maps of the Precambrian complexes [Zaritsky, A.I., Galetsky, L.S. (Eds.), 1992. Geology and Metallogeny of the Southwest of the East-European Platform Map Series, 1 : 1,000,000, Ukrainian State Committee on Geology and Utilization of Mineral Resources, Kiev.] is largely obstructed by a cover of post-Palaeozoic sediments and soils of variable thickness. This obstruction is aggravated by an almost continuous patchwork of farmlands. However, analysis of the current drainage patterns in the Dniepr River basin and surrounding regions reveals a spatial coincidence of numerous stream courses and watersheds with previously inferred steep, transcrustal discontinuities of most probably Precambrian age.

Transcrustal dislocations constituted important pathways for heat and fluids as is indicated by the distribution of a large proportion of assumed Early Proterozoic hydrothermal iron and gold deposits along them. This distribution is underpinned by the spatial coincidence of mineralization and elongate areas of highly irregular magnetization attributed to uneven distribution of hydrothermal magnetite in banded iron formation. In view of the extent of these dislocations, both vertically and laterally, the generation of hydrothermal fluid flow, emplacement of mantle-sourced magma and associated mineral potential away from banded iron formation complexes is likely. A second group of gold deposits, of Archaean age, is known to occur in association with still recognizable volcanic edifices in greenstone complexes. It is not known if and to what extent such Archaean gold deposits are related to these major transcrustal discontinuities. The kinematics and dynamics of these dislocations and pathways appear largely unknown and deserve high-priority investigation. The geological longevity of the transcrustal dislocation framework till the present day inferred from the current drainage systems is corroborated, however, by repeated regional topographical levelling surveys.

Keywords: East European Platform; Precambrian; Iron; Gold; Moho; Crust; Structure; Drainage patterns

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1. Introduction

The southwestern East European Platform is underlain by the Precambrian complexes of the Ukrainian Shield and the Voronezh Massif to the south and to the north of the Pripyat–Dniepr–Donets rift, respectively (Fig. 1). These are thought to belong to one and the same coherent, though very complex, Sarmatian Segment of the East European Craton (Bogdanova, 1993; Gorbatschev and Bogdanova, 1993; Bogdanova et al., 1996; Shchipansky and Bogdanova, 1996). On regional maps, the Ukrainian Shield and the Voronezh Massif are often shown as outcrops of Precambrian basement but both have a cover of Mesozoic and Cenozoic sediments and soils of variable thickness. In the depression intervening between the two principal massifs, the basement underlies a column of Palaeozoic and Mesozoic sediments of up to 22 km in the about 2000 km long ESE-striking Pripyat–Dniepr–Donets (PDD) rift. Over the past fifteen years the rift has been the subject of substantial and locally detailed investigations whose results have been published in English (e.g., Stephenson et al., 1993, 2001; Maystrenko et al., 2003; Grad et al., 2003; Saintot et al., 2003).

The vast literature on the Precambrian formations is mainly in Russian, but the results of decades of geological and geophysical investigations are summarized by Zaritsky and Galetsky (1992) in a series of maps at 1:1,000,000 scale with geographical coordinates and with legends in English. We studied Landsat imagery in an attempt to complement this geological and geophysical information and to tie it in with readily recognizable topographic configurations with a view to clarify the setting of a number of ore deposits. Depending on the thickness of cover material the imagery was expected to reflect shallow structural and lithological configurations of the cover sediments and of the Precambrian complexes. The PDD rift structure was, intuitively, expected to be clearly expressed in the morphology of the region. Over most of the southwestern East European Platform of Ukraine and southern Russia, however, Landsat imagery (ESDI, 2004; University of Maryland, 2004; NASA Applied Sciences Directorate, 2005) shows a dominant patchwork of farmlands transected by roads, rivers and small streams. Therefore, geological interpretation of the imagery in terms of Mesozoic and Cenozoic rock types, let alone the lithology and the structures of the underlying Precambrian and Palaeozoic basement, was not feasible. The spectral characteristics of the fields, however, are relatively homogeneous while those of the alluvial sediments of the drainage network are more diverse. Consequently the farmlands can be suppressed while enhancing the drainage systems by subtracting the signatures of the farmlands. Surprisingly, the resulting patterns of dissection by the principal rivers and their tributaries in many areas suggest correlation with deep-reaching structural discontinuities shown on the 1:1,000,000 scale maps of the Precambrian basement complexes (Zaritsky and Galetsky, 1992), rather than shallow structures and lithology. In this study we continue with the drainage patterns drawn on the above geological and geophysical maps in conjunction with the digital terrain model (Fig. 2) provided by the global Shuttle Radar Topography Mission (SRTM3, 2004). This circumvents the time-consuming processing and matching of the about 50 Landsat Thematic Mapper (TM) frames that cover the southwestern East European Platform. We pursue the relationships between the distribution of Precambrian gold and iron deposits, deep-seated structure and drainage systems.

2. Methods

Central to our analysis is the Geology and Metallogeny of the Southwest of the East European Platform 1:1,000,000 Scale Map Series (Zaritsky and Galetsky, 1992). The map sheets were scanned and saved in tiff format, joined in Adobe Photoshop®, converted to image files, geocoded on one-degree intersections and projected to UTM zone 36 WGS84 in Erdas Imagine 8.7®. They were analysed by visual examination with ArcMap® software in conjunction with the SRTM3 database (SRTM3, 2004), and the Magnetic Map of Europe, 1:5 000 000 (Simonenko and Pashkevitch, 1990). We digitally traced the principal streams of the 1:1,000,000 scale map (Chekunov et al., 1992a) in order to bring out the drainage patterns in the flat areas on the one hand and in verification of the compatibility of these maps with the SRTM3 digital terrain model on the other. Invariably, the stream courses derived from the maps agree well with the SRTM3 database within the grid of controlling one-degree intersections (Fig. 2). In view of the differences in the interpretation of the nature, extent and structure of the near-surface Precambrian complexes (e.g., Zaritsky and Galetsky, 1992; Shchipansky and Bogdanova, 1996; Pastukhov, 1993; Yegorova et al., 2004), which can only very locally be resolved by the available imagery, our analysis revolves primarily about previously inferred steep discontinuities (Chekunov et al., 1992a). These structures are transcrustal in part since locally they are inferred to displace the Moho. To our knowl-

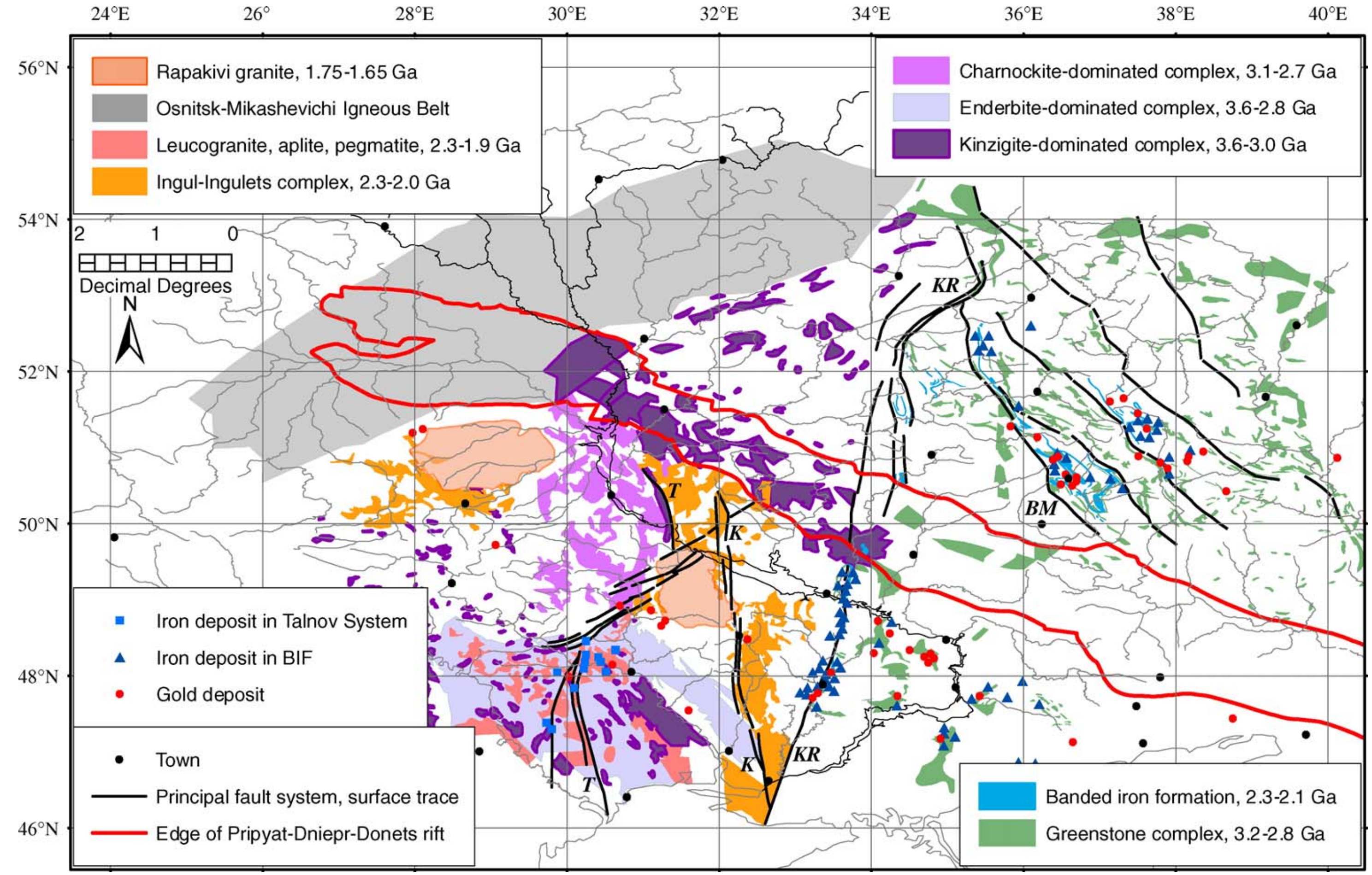

Fig. 1. Distribution of geological complexes discussed in the text, after Kolosovskaya et al. (1992a). T—Talnov Suture, K—Kirovograd Thrust, KR—Krivoi Rog Suture Zone, BM—Belgorod–Mikhailov Thrust. Towns are identified in Fig. 2. One degree of latitude and longitude corresponds to approximately 110 km.

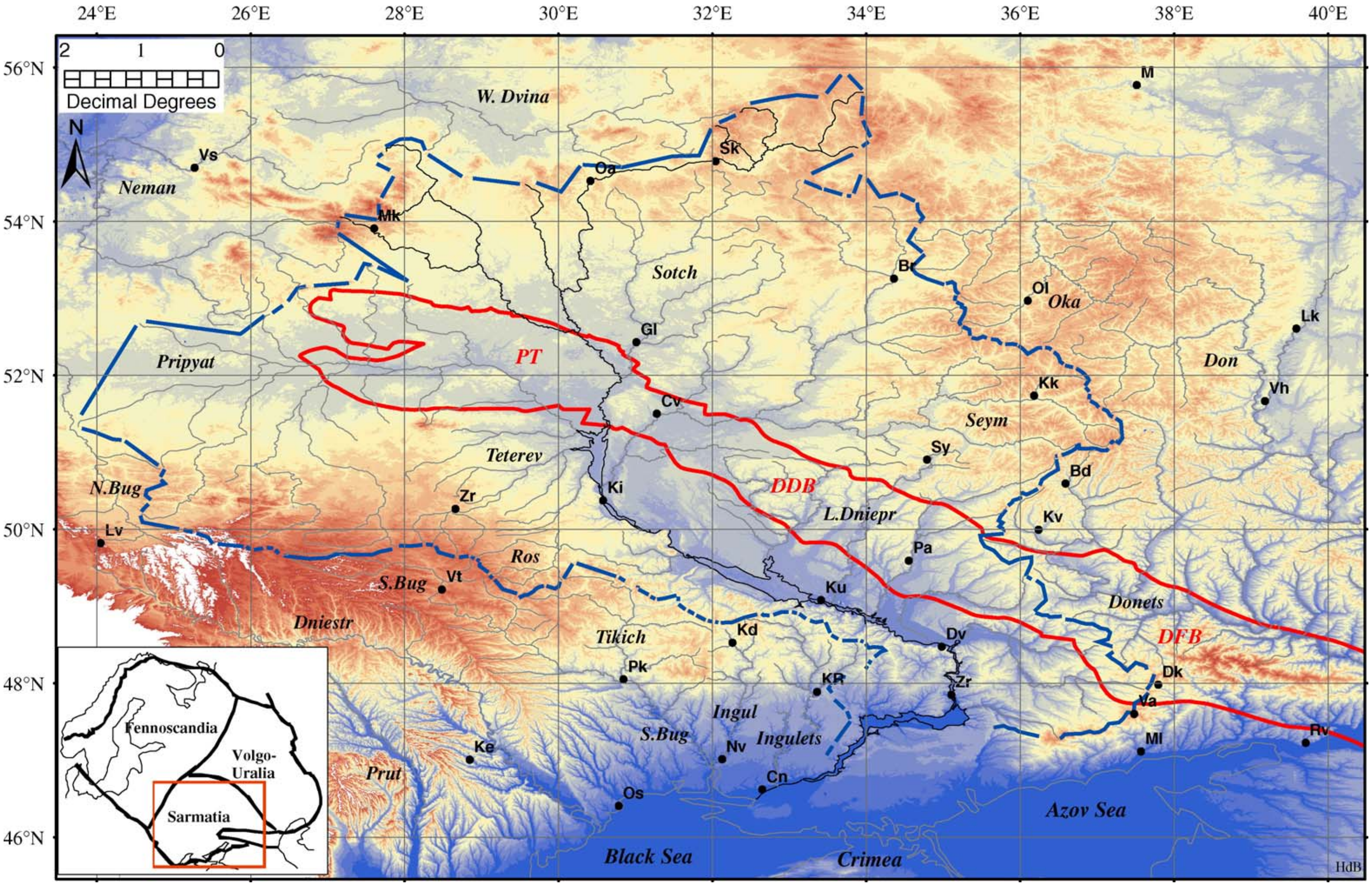

Fig. 2. Digital elevation model (SRTM3, 2004) of the southwestern East European Platform with principal divide of the Dniepr River Basin (heavy blue line) and outline of the Pripyat–Dniepr–Donets rift (heavy red line). The main Dniepr–Berezina River system is in black; all other rivers are in grey. Names of tributary and external catchment areas are in italics. White areas are over 350 m a.s.l. Projection—WGS84 UTM Zone 36. Towns: Bd—Belgorod, Bk—Briansk, Cv—Chernigov, Cn—Cherson, Dk—Donetsk, Dv—Dniepropetrovsk, Gl—Gomel, Kd—Kirovograd, Ke—Kischinev, Ki—Kiev, Kk—Kursk, Ku—Kremenchuk, Kv—Kharkov, KR—Krivoi Rog, Lk—Lipetsk, Lv—Lvov, M—Moscow, Mk—Minsk, Ml—Mariupol, Nv—Nikolaev, Oa—Orsha, Ol—Orel, Os—Odessa, Pa—Poltava, Pk—Pervomaisk, Rv—Rostov, Sk—Smolensk, Sy—Sumy, Va—Volnovakha, Vh—Voronezh, Vs—Vilnius, Vt—Vinnitsa, Zr—Zhitomir, Zz—Zaporozhye. Segments of Pripyat–Dniepr–Donets rift: PT—Pripyat Trough, DDB—Dniepr–Donets Basin, DFB—Donets Fold Belt. One degree of latitude and longitude corresponds to approximately 110 km. Inset: Location in relation to the three-segment subdivision of the East European Craton after Gorbatschev and Bogdanova (1993).

edge, studies on the kinematics of these structures are not yet available.

The uncertainties in the interpretation of the metamorphic complexes, in terms of their protoliths and their original setting, ages, deformation and interrelationships, are magnified by lateral discontinuity due to limited outcrop. Given this, a systematic overview of crustal complexes and their evolution is beyond the scope of this paper. Instead, from the confidence in previously inferred Moho features and transcrustal discontinuities (Chekunov et al., 1992a) which we derive from the spatial correlation with current drainage patterns, we attempt a correlation between Moho domains and selected features of upper crust complexes and hydrothermal iron and gold deposits (Kolosovskaya et al., 1992a,b), with a view to ultimately decipher the dynamics of the crust, upper mantle and mineral resources with reference to common cartographic coordinates.

3. Geological setting

Both the Ukrainian Shield to the south and the Voronezh Massif to the north of the ESE-striking Palaeozoic Pripyat–Dniepr–Donets (PDD) rift (Fig. 1) contain Archaean elements, large areas of which were reworked by Palaeoproterozoic deformation and metamorphism. Together with the Osnitsk–Mikashevichi Igneous Belt (OMIB) in the northwest, the Ukrainian Shield and the Voroneh massif constitute the Sarmatian Segment of the East European Craton (Fig. 2 inset). The OMIB consists of 2.02–1.98 Ga plutono-volcanic complexes. According to Bogdanova et al. (2004) the magmatism may reflect an active continental margin and subduction of oceanic crust beneath the Sarmatian protocraton. The Sarmatian Segment is separated from the Fennoscandian and Volgo-Uralian Segments of the East European Craton by Meso- and Neoproterozoic (Riphean) rifts that follow Palaeoproterozoic sutures and junction zones (Gorbatschev and Bogdanova, 1993; Bogdanova et al., 1996).

Shchipansky and Bogdanova (1996) show the Sarmatian Segment to consist of a number of independent crustal blocks symmetrically laid out with respect to the central, about NNE-striking, Krivoi Rog Suture Zone (KRSZ). The boundaries between the major units represent northerly striking deep crustal discontinuities. The distribution of blocks, microcontinents and terranes and of their interrelationships shown in the small-scale conceptual diagrams of the above publications can, however, only in part be traced on the regional geological maps by Zaritsky and Galetsky (1992), due in part to large-scale shallow-dipping imbricate thrust stacks which complicate the relationships between Archaean basement and Proterozoic belts. The lithologies and distribution of the Precambrian complexes are treated in detail by Malyuk (2001).

In the western part of the Ukrainian Shield a subdivision stands out between a complex of enderbite, migmatite, khondalite, granodiorite, diorite and plagiogranite with dominantly Archaean ages (3.6–2.8 Ga) to the south and a complex of charnockite, migmatite and leucogranite with dominantly Palaeoproterozoic ages (2.4–1.9 Ga) to the north (Fig. 1). The transition between these is in a narrow belt at the latitude of Kirovograd which can be traced from west to east for ca. 200 km. In the northern part the westernmost occurrences of the 2.3–2.0 Ga Ingul–Ingulets complex occur with rhythmically banded biotite- and graphite-bearing schists and gneisses which are interpreted as metasiltstone and metasandstone (Kolosovskaya et al., 1992a). This complex is prominent in the central part of the Ukrainian Shield. Here the Ingul–Ingulets complex is delimited to the north by an approximately 400 km long belt with ESE strike of fault-bounded blocks of Archaean kinzigite complexes (3.6–3.0 Ga). These blocks appear embedded in a regional matrix of 2.3–1.9 Ga biotite–garnet granite and migmatite. To the east, the Ukrainian Shield and the Voronezh Massif are characterized by complexes of greenstone and banded iron formation. The easternmost part of the Voronezh Massif, largely outside the map of Fig. 1, comprises of the Lipetsk–Lozev Volcanic Belt with widespread metavolcanics of island arc affinity and the metapelitic and metapsammitic schists (metaturbidites) of the East Voronezh Province. Together these are thought to represent a major Palaeoproterozoic orogenic belt along the junction of the Sarmatian and Volgo-Uralian Segments (Shchipansky and Bogdanova, 1996).

The two-fold division into Ukrainian Shield and Voronezh Massif by the Palaeozoic PDD rift is based on earlier ideas interpreting an older structural discontinuity as a locus of Riphean rifting (e.g., Chekunov et al., 1992b). However, the existence of a Riphean rift below the Palaeozoic rift has not been substantiated (Stovba and Stephenson, 1999). In addition, transcurrent crustal deformation along the rift zone has been invoked as a dividing element between the Ukrainian Shield and the Voronezh Massif (e.g., Arthaud and Matte, 1977). However, Shchipansky and Bogdanova (1996) conclude continuity of Precambrian structures from the Ukrainian Shield to the Voronezh Massif. According to Ziegler (1989) Mid-Devonian subsidence relates to back-arc extension associated with the Variscan geosynclinal system. Wilson (1993) and Wilson and Lyashkevitch (1996) attribute the rift to a Devonian mantle plume. Recent investigations by Saintot et al. (2003) in the inverted Donets segment of the rift (Donbas Fold Belt, DFB, Fig. 2) arrive at Devonian and Early Visean NNE–SSW extensional and Early Permian NW–SE transtensional deformation. The Early Permian deformation included pronounced, kilometer-scale, uplift of the southern margin of the rift and the Ukrainian Shield (Stovba and Stephenson, 1999; Stephenson et al., 2001; Saintot et al., 2003). Saintot et al. (2003) suggest inversion of the Donets segment during the Cretaceous/Palaeocene. Privalov (1998) and Privalov et al. (2002) favour a dominantly Permian age of thrusting and folding (see also Spiegel et al., 2004). The driving mechanisms remain uncertain (Saintot et al., 2003). In particular the conclusions of Shchipansky and Bogdanova (1996) suggest the morphology (Fig. 2) of the two principal Precambrian units, Ukrainian Shield and Voronezh Massif, must relate to Devonian and Permo-Carboniferous deformation rather than to Precambrian complexity.

4. Distribution of gold and iron deposits

A large proportion of the known ore deposits and mineral showings occurs in clusters that are spatially associated with specific lithological complexes and structural discontinuities (Figs. 1 and 3). Conspicuous clusters are in the greenstone complexes east of the Krivoi Rog Suture Zone. Other major clusters occur in the area west and north of Pervomaisk and east and south of Kirovograd in the western and central Ukrainian Shield (Fig. 3).

According to Chernyshov and Myasnyankin (1992), the gold-bearing mineralization of the eastern Voronezh Massif occurs exclusively within the Early Proterozoic clastic–volcanic Tim suite. The clastic–carbonate Rog suite and overlying Tim suite constitute the Oskol series which overlie the Kursk series of clastic and chemical sediments, including major banded iron formation deposits. The mineralized zones show multiple phases of intense deformation along major regional thrusts and deep-reaching fault zones and highly varied ultramafic to granitic magmatic complexes. Prominent alteration zones are suggested to reflect massive fluid–rock interaction. The clastic and chemical sediments of the Early Proterozoic Kursk series were deposited in basins overlying Late Archaean rift structures and their greenstone belts. Shchipansky and Bogdanova (1996) also locate the banded iron formation deposits of the Voronezh Massif and of the Ukrainian Shield (Krivoi Rog) in the Kursk series. They distinguish two groups, in interior basins and marginal basins, with respect to their inferred location on and along Archaean cratons. As in the case of the gold mineralization of the eastern Voronezh Massif, hypogene fluids affected the banded iron formation deposits along the Krivoi Rog Suture Zone. Here, fluid–rock interaction resulted in hypogene magnetite deposits which formed the protores to the supergene enriched ores that are now mined (Belevtsev et al., 1983; Dalstra and Guedes, 2004). In turn, the iron ore deposits in the Kursk series, stratigraphically below the Oskol series on the eastern Voronezh Massif, and gold deposits along the Krivoi Rog Suture Zone in the Ukrainian Shield may have been derived from the same processes. All the above gold and iron deposits occur in zones of highly variable magnetization (Fig. 3) which may be the result of irregular distribution of magnetite formed by high-temperature fluid–rock interaction (Belevtsev et al., 1983; Dalstra and Guedes, 2004). In turn this establishes the Krivoi Rog Suture Zone and the thrust belts in the Voronezh Massif as Proterozoic crustal-scale fluid conduits with a lateral extent of at least 500 and 250 km, respectively.

In addition to the three gold prospects shown close to the Krivoi Rog Suture Zone, near Krivoi Rog, nine gold deposits are located further east in spatial association with greenstone complexes in which volcanic edifices are locally preserved. Five occur in the Sura greenstone unit, ca. 25 km southwest of Dniepropetrovsk. Here, Bobrov et al. (2001a) refer to 3.20–3.05 Ga rhyodacite–plagiogranite volcano-plutonic associations with irregular stockworks and stratiform, stratabound lens-shaped gold deposits and prospects related to banded iron formation and mafic volcanic complexes.

Yatsenko et al. (2001) report four gold fields within the N-striking Kirovograd Thrust (Kirovograd district with Klyntsi–Koniv metallogenic zone). The steeply dipping mineralized belt is shown to extent at least 100 km with a width up to ca. 10 km (Fig. 3). The Klyntsi gold deposit is located about 20 km southeast of Kirovograd. Strong deformation and intense hydrothermal alteration affected the host rock. The mineralized belt is located in biotite gneisses (metagraywackes) of the Proterozoic Ingul–Ingulets complex.

Bobrov et al. (2001b) describe the regional setting of the Maiske gold district in the 15–20 km wide deep-seated Odessa–Talnov fault zone and its local setting in a leucogranulite association. The district, with a strike length of some 17 km in the northern part of this southern branch of the Talnov Suture, comprises the Maiske deposit and five prospects. Merkushin et al.

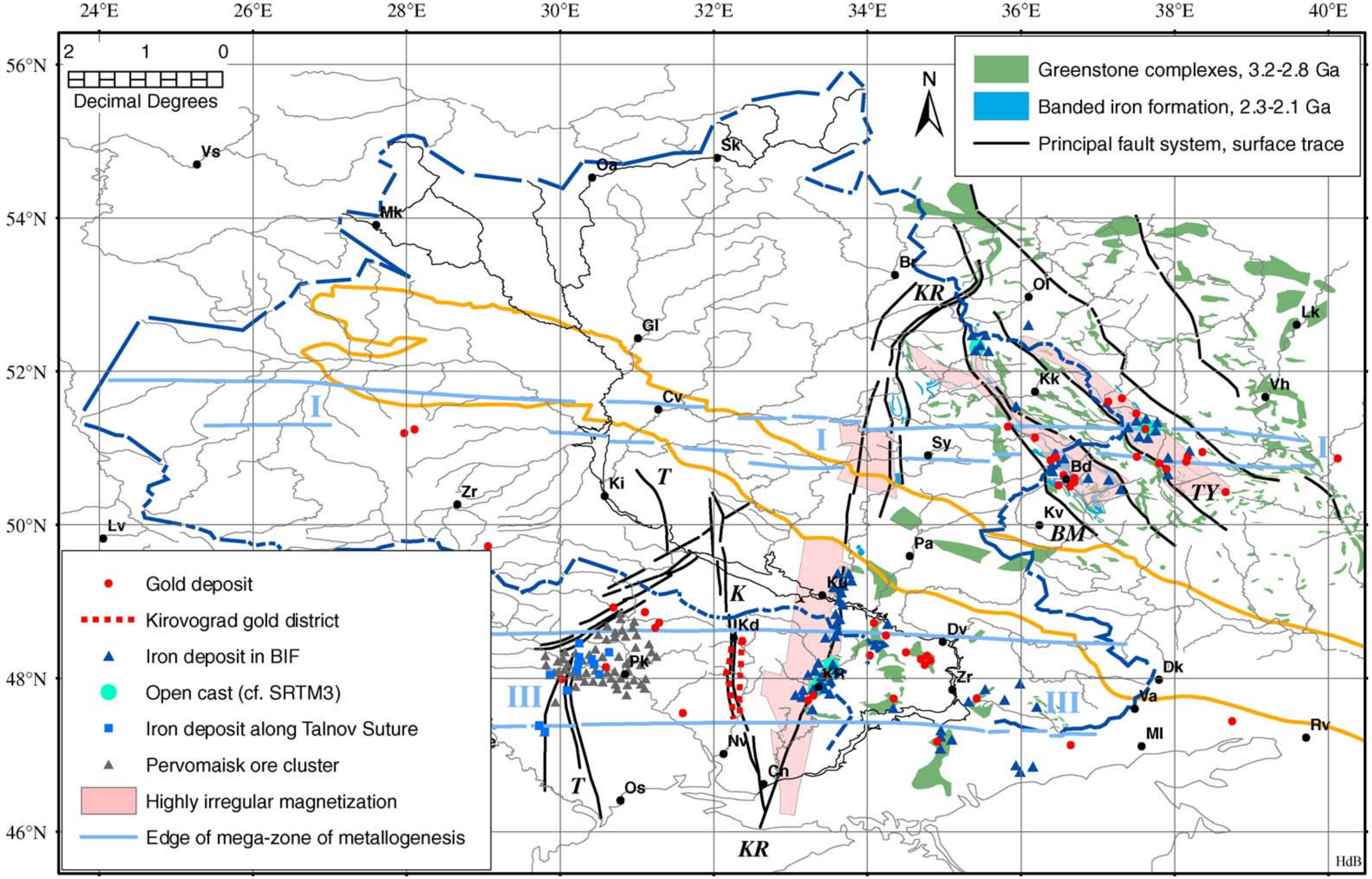

Fig. 3. Distribution of ore deposits discussed in the text, after Kolosovskaya et al. (1992b). The Pervomaisk ore cluster is not differentiated. T—Talnov Suture, K—Kirovograd Thrust, KR—Krivoi Rog Suture Zone, BM—Belgorod–Mikhalov Thrust, TY—Tim–Yastrevo Thrust. Towns are identified in Fig. 2. One degree of latitude and longitude corresponds to approximately 110 km.

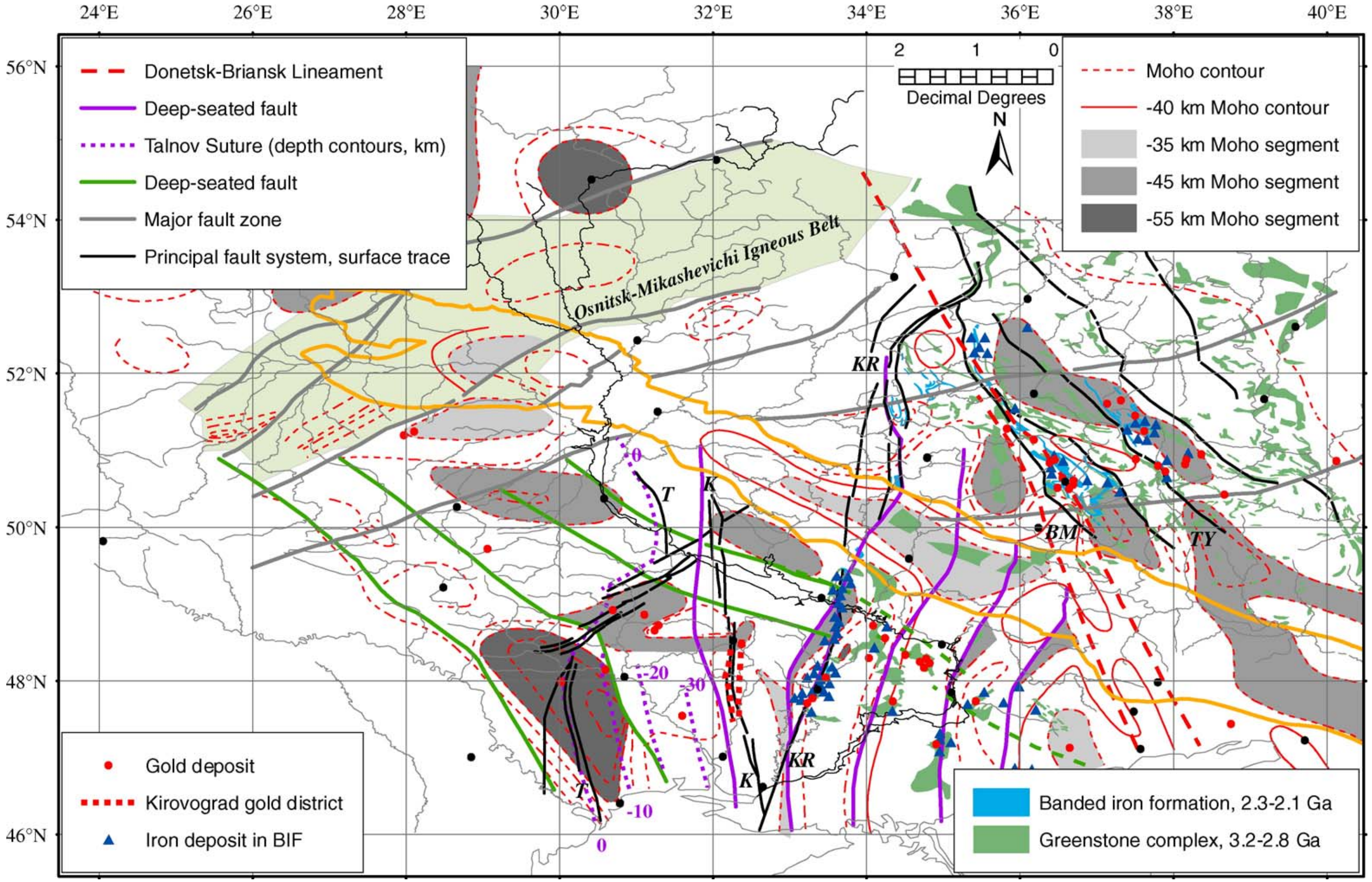

Fig. 4. Deep-seated structure after Chekunov et al. (1992a). Lithological complexes, major fault zones and surface traces of principal fault systems are after Kolosovskaya et al. (1992a). Ore deposits are after Kolosovskaya et al. (1992b). T—Talnov Suture, K—Kirovograd Thrust, KR—Krivoi Rog Suture Zone, BM—Belgorod–Mikhalov Thrust, TY—Tim–Yastrevo Thrust. Towns are identified in Fig. 2. One degree of latitude and longitude corresponds to approximately 110 km.

(2001) detail the paragenesis of the Maiske deposit and its cooling history from about 450 °C. Sivoronov et al. (2001) list five stages in an ore-petrological model spanning some 1.5 billion years.

The cluster of ore deposits west of Pervomaisk (Fig. 3), along the central part of the Talnov Suture, comprises four mesothermal gold deposits and nine iron deposits, i.e., two skarn and seven metamorphosed, but otherwise unspecified deposits. In addition, graphite deposits, tungsten-bearing skarns, nickel and nickel–copper, and rare earth and phosphate deposits are known (Kolosovskaya et al., 1992b). The area of the cluster measures ca. 90 by 130 km and centres on a body of leucogranite with a diameter of ca. 60 km. Smaller bodies of the leucogranite occur within the cluster mostly along the shears of the Talnov Suture. Intrusions of ultramafic rocks, with diameters up to 2 km, are conspicuous within and along the edges of the leucogranite bodies. Together these suggest massive fluid–rock interaction and a material input from the mantle. In this area elongate bodies of calciphyre and gneiss are shown measuring up to 5 by 20 km. Calc-silicate rocks (probably original carbonatite) constitute only a minor part of the associations which probably represent metamorphosed and deformed volcano–sedimentary complexes (I. Mudrovska, pers. comm., 2005). The complex occurs along a bend in the Talnov Suture where it overlies a system of WNW- to NW-striking steep discontinuities (Fig. 4) that vertically offset the Moho and where the Talnov Suture may disrupt the Moho surface along a NE-striking zone (Fig. 4).

Stein et al. (1999) report Re–Os ages of molybdenite in two gold deposits in the Ukrainian Shield. The Sergeevka deposit is in a volcano–plutonic complex southwest of Dniepropetrovsk. Here the Re–Os age of associated molybdenite is 3.128 ± 0.013 Ga. At Maiske, gold and molybdenite occur in quartz veins and pegmatites that are younger than the migmatites. The associated molybdenite has an age of 2.060 ± 0.009 Ga. These two different ages indicate two stages of gold mineralization but leave the above fluid–rock interaction in the Belgorod–Kursk region and along the Krivoi Rog Suture Zone undated.

Kolosovskaya et al. (1992b) show sixteen structural–metallogenic zones and six linear mega-zones in which metal concentration is thought to have occurred episodically. The structural–metallogenic zones clearly relate to sutures between different regional-scale units. The mega-zones on the other hand are shown as corridors of repeated metallogenesis that developed across the regional units. Two of these (Fig. 3), with east–west strike, merit attention in the context of the present study. The northern mega-zone (I, Ukrainian–Voronezh) spans the Dniepr River Basin from its western apex to the Voronezh area in the east with a length in the order of 1600 km and a width of about 70 km. The southern mega-zone (III, southern Ukrainian) is located at the latitude of Pervomaisk and Krivoi Rog and has a length of about 750 km and a width of about 125 km. Both cut across the Precambrian complexes. Although without a clear relation with the major tectonic discontinuities, both mega-zones contain a number of E-striking faults of variable length shown by Kolosovskaya et al. (1992a) and Moho features shown by Chekunov et al. (1992a). These zones do contain prominent ore deposits like the iron and gold deposits near Krivoi Rog and between Belgorod and Kursk. However, the primary control of the gold deposits east of the DBL appears in their association with greenstone complexes close to banded iron formation horizons. Although this ore deposit distribution, even with the coincident E-striking fault zones, does not clarify the prominent metallogenic mega-zones, the present study tends to lend weight to their reality with the recognition of major structural corridors by means of some of the drainage systems (see Section 6.2 and Fig. 7).

5. Deep-seated structure

Between Mariupol, on the coast of the Azov Sea, and Briansk, to the north-northwest, Moho contours (Fig. 4) define an approximately 900 km long discontinuity in the pattern which is interpreted by Chekunov et al. (1992a) as a steep, deep-seated dislocation. This is known as the Donetsk–Briansk Lineament (DBL; Kutas and Pashkevitch, 2000). Where this structure crosses the PDD rift domain it suggests a threshold between the Dniepr–Donets rift segment to the west, with the Moho at about −35 km, and the Donets segment with the Donets Fold Belt, where the Moho is located at about −45 km. Here, however, recent seismic experiments (Maystrenko et al., 2003) suggest a deep-seated shallow-dipping thrust whose strike is approximately parallel to the axis of the rift and which affects the Moho. According to Stovba and Stephenson (1999) the DBL structure is not expressed by the sedimentary fill of the rift.

East of the DBL, Moho contours have a southeasterly trend which swings to a south-southeasterly orientation towards the DBL to conform to the trace of the lineament. These Moho trends conform to those expressed by the structures in the near-surface greenstone and banded iron formation complexes (Fig. 4). West of the DBL, the most prominent configuration of

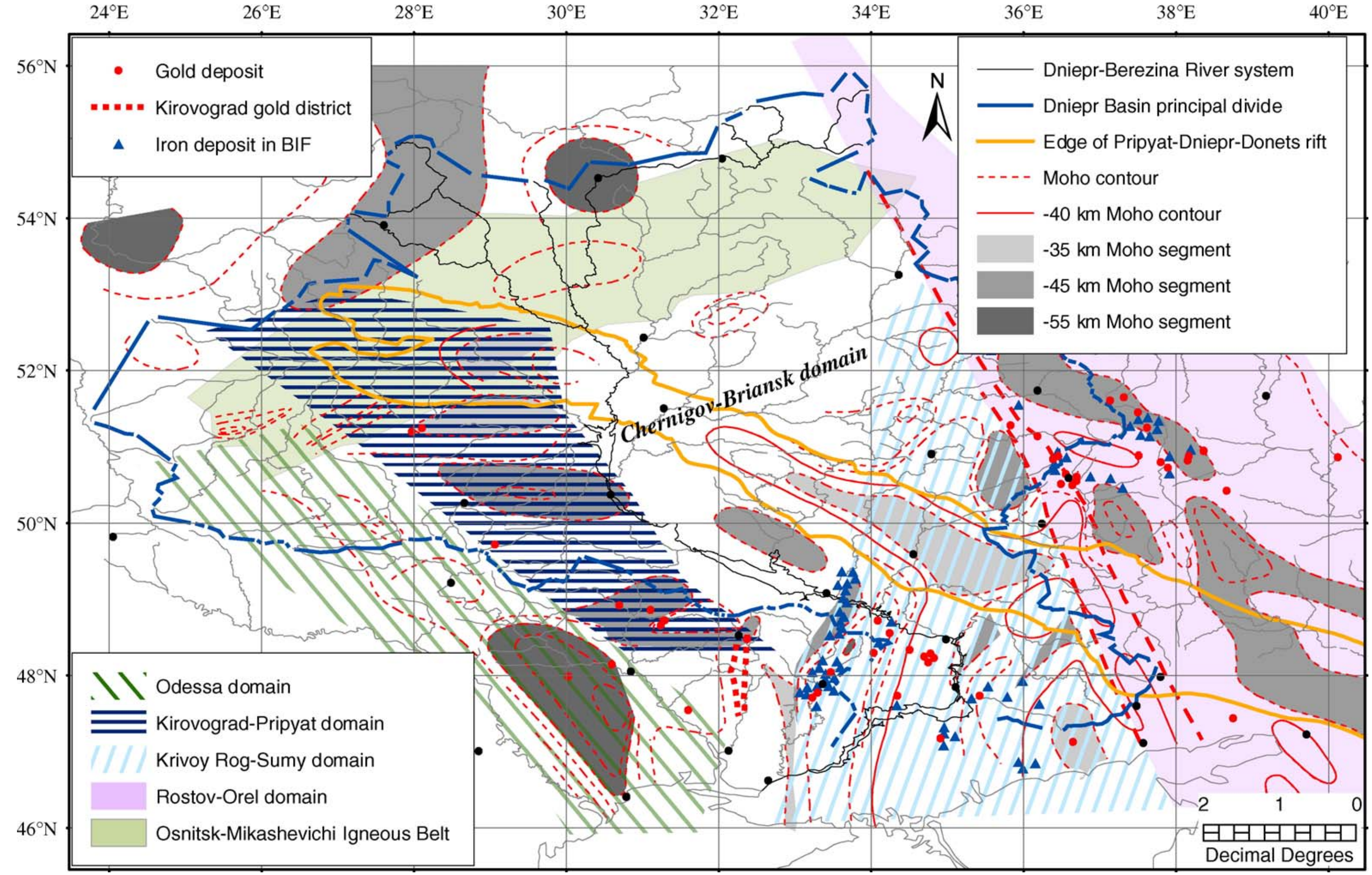

Fig. 5. Dniepr River Basin and surrounding regions with regional-scale domains based on Moho morphology after Chekunov et al. (1992a). Ore deposits after Kolosovskaya et al. (1992b). Towns are identified in Fig. 2. One degree of latitude and longitude corresponds to approximately 110 km.

the Moho contours runs parallel to the Pripyat and Dniepr segments of the PDD rift where the Moho shallows to about −35 km. Less conspicuous but significant features are NNE-striking discontinuities in the Krivoi Rog–Zaporozhye area along which the Moho is vertically displaced and therefore are of transcrustal nature. The westernmost of these is the Krivoi Rog Suture Zone which can be traced for approximately 600 km to the Briansk area north of the PDD rift. ESE- to SE-striking transcrustal discontinuities are conspicuous in the central Ukrainian Shield. E-striking elongate closed Moho contours are very notable along the rift, particularly in the area of the Pripyat segment in the west.

The steep Kirovograd Thrust (Fig. 4) extends at least 500 km northward from the Black Sea coast near Nikolaev. Kolosovskaya et al. (1992a) place the near-surface trace about 25 km further east. Grad and Tripolsky (1995) infer its transcrustal nature. West of the Kirovograd Thrust, the Talnov Suture extends over a distance of about 530 km from the coast to the north (Fig. 4). Chekunov et al. (1992a) show it as a major eastward dipping structure with depth contours down to −30 km on its southern part. This discontinuity crosscuts the SE-striking over 60 km thick crustal welt along the western margin of the Ukrainian Shield northwest of Odessa. The central, NE-striking part of the Talnov Suture is known as the Talnov Shear. This overlies and parallels a −45 km elongate closed Moho contour.

The regional Moho pattern (Chekunov et al., 1992a) leads to the recognition of six regional-scale domains (Fig. 5). These are, from west to east:

- a westernmost Odessa domain, defined by SE-striking discontinuities in the Moho and a pronounced thick crustal welt northwest of Odessa;
- a Kirovograd–Pripyat domain, defined by E-striking elongate closed Moho contours, in the surface geology only seen in the E-striking orientation of the Palaeozoic Pripyat Trough; this domain corresponds roughly to the axial belt of the SE-striking Kirovograd orogenic belt (Galetsky and Pastukhov, 1993) which cannot, however, be clearly extracted from the map by Kolosovskaya et al. (1992a);
- a central Chernigov–Briansk domain, without distinct Moho features, apart from those associated with the Dniepr–Donets Basin, with dominant northerly internal grain in the near-surface complexes (e.g., Lazko et al., 1989);
- a Krivoi Rog–Sumy domain, with clearly defined NNE-striking strips in the lower crust enhanced by fault-bounded Moho segments;
- an eastern Rostov–Orel domain, with its SE- to SSE-striking elements in both the Moho and in the near-surface lithologies and structures, set apart from the above domains by the DBL; and
- an Osnitsk–Mikashevichi domain in the northwest, discordantly and disharmoniously extending across the other domains.

6. Drainage patterns

The outstanding hydrographical feature of the southwest East European Platform is the basin of the Dniepr River. It has a roughly triangular outline with its apices in the Lvov area in the west, the Smolensk area in the north and the Mariupol area in the southeast, on the coast of the Azov Sea (Figs. 2, 3, 5, 6 and 7). Its surface measures about 700,000 km^2. Within the basin, seven tributary catchment regions occur. Both the watersheds of the main basin and of the internal catchments, together with the individual courses of some of the rivers, appear to overlay deep-seated dislocations and/or major lithological complexes.

6.1. Principal divides of the Dniepr River Basin

Surrounding the Dniepr River Basin there are three principal river systems (Figs. 2 and 6) which drain

1. to the west and north: of the northern Bug, Neman, and western Dvina Rivers
2. to the east: of the Donets, Don, and Oka Rivers
3. to the south: of the Prut, Dniestr, southern Bug, Ingul, and Ingulets Rivers.

The watersheds between these three systems and the Dniepr River Basin are underlain, respectively, by the NE-striking Osnitsk–Mikashevichi Igneous Belt in the northwest, four ESE-striking fault lines in the south and the NNW-striking Donetsk–Briansk Lineament in the east. Their strike parallels grain or discontinuity of the Moho morphology. The Dniepr River cuts through the southern watershed between Dniepropetrovsk and Zaporozhye, in the area underlain by NNE-striking transcrustal dislocations, from where it discharges to the Black Sea (Fig. 6). Between Kiev and Dniepropetrovsk, the valley of the lower Dniepr strikes parallel to the PDD rift but is, counterintuitively, located to the south of the rift structure between two ESE-striking fault lines (Fig. 6).

The western part of the southern divide is defined by the tributary catchments of the Pripyat, Teterev and Ros Rivers and the external catchments of the S. Bug,

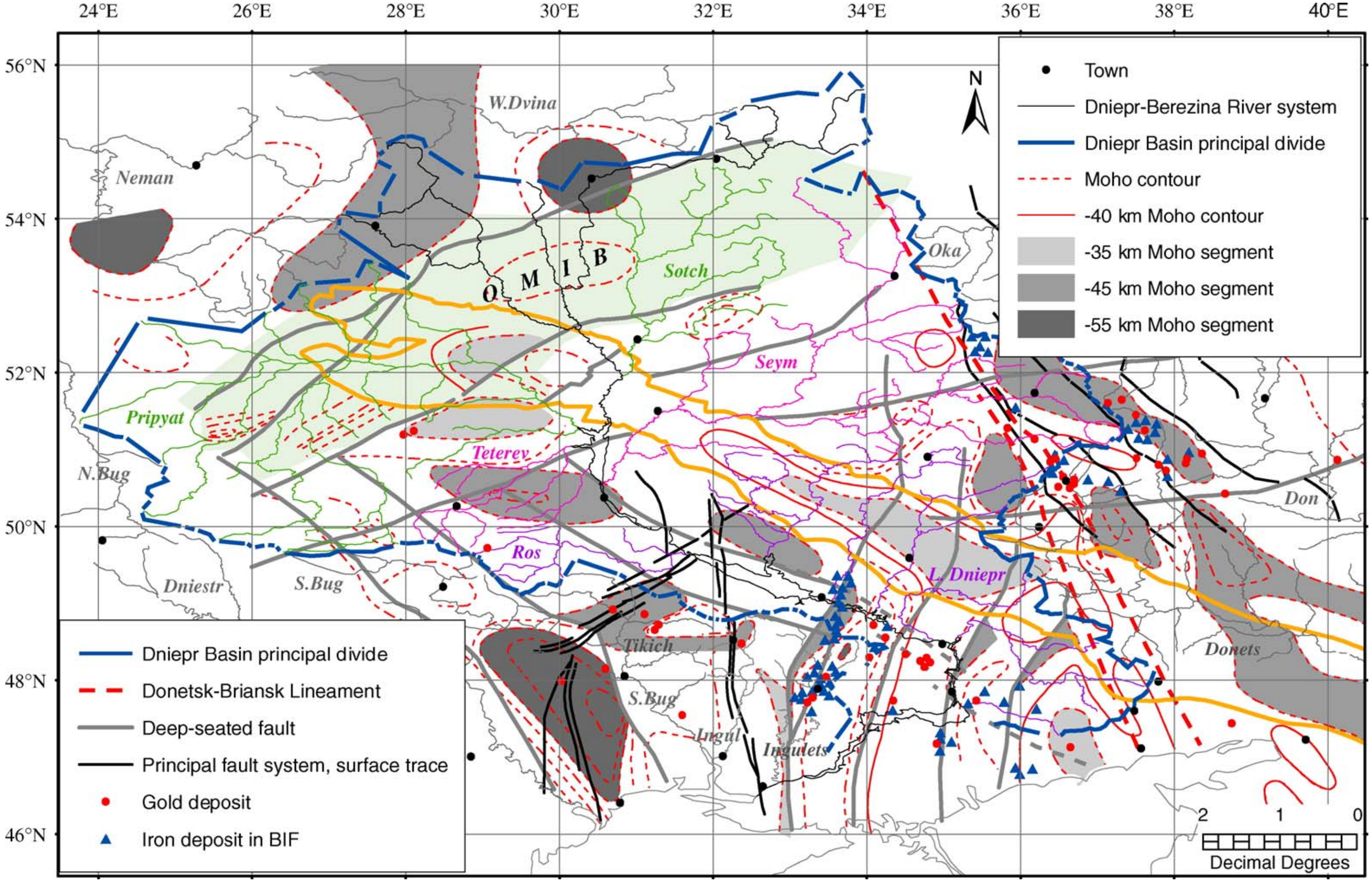

Fig. 6. Dniepr River Basin, tributary and external catchment areas (in italics) in relation to deep structure after Chekunov et al. (1992a). Ore deposits after Kolosovskaya et al. (1992b). OMIB—Osnitsk–Mikashevichi Igneous Belt. Surface traces of principal fault systems are identified in Figs. 3 and 4. For town names see Fig. 2. One degree of latitude and longitude corresponds to approximately 110 km.

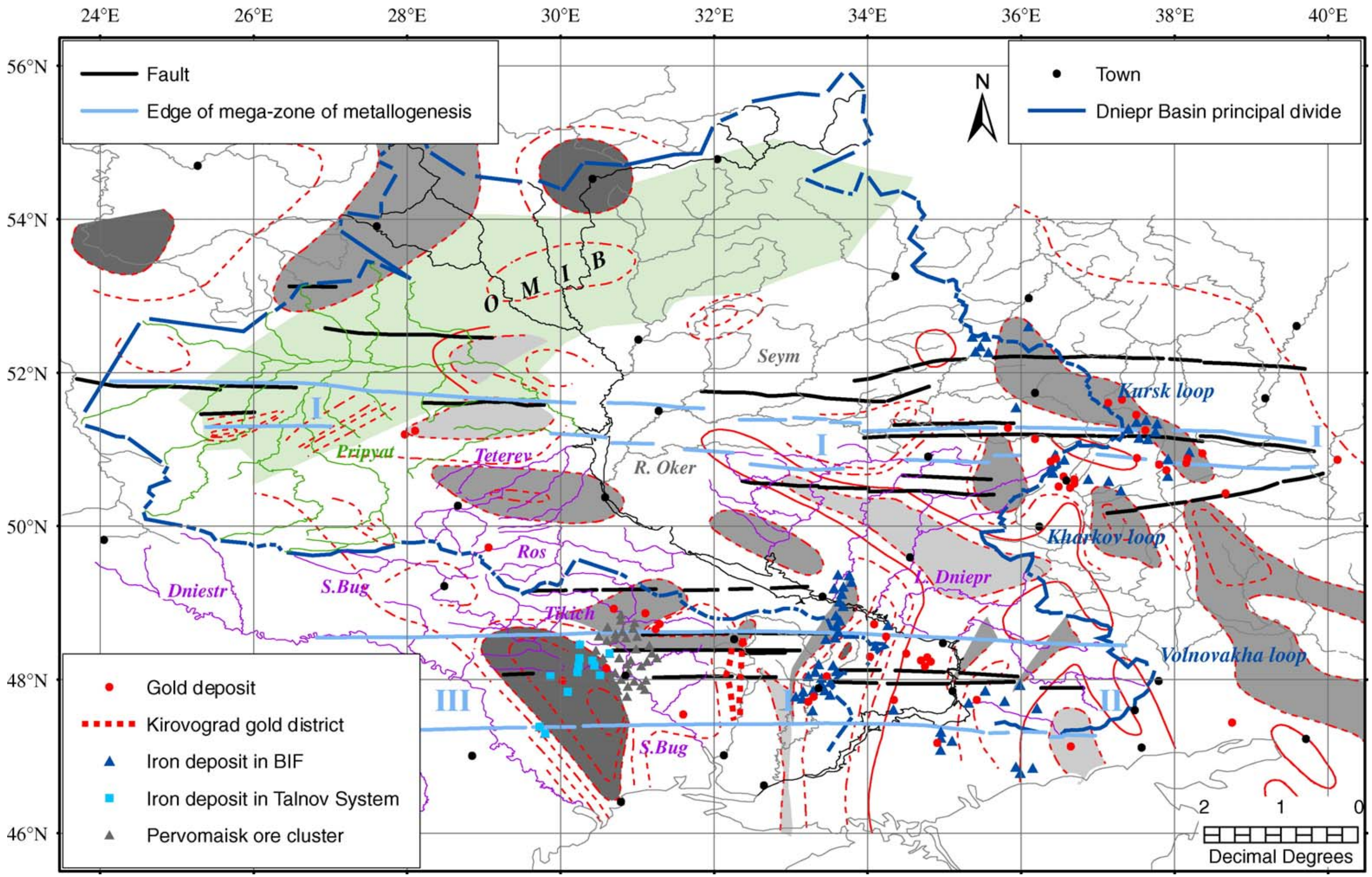

Fig. 7. Catchment areas (in italics) with prominent E-striking river courses in relation to E-striking faults (after Kolosovskaya et al., 1992a), mega-zones of metallogenesis (I and III) and ore deposits (after Kolosovskaya et al., 1992b), Moho morphology (after Chekunov et al., 1992a; see legend to Fig. 6) and the Kursk, Kharkov and Volnovakha loops in the eastern watershed of the Dniepr River Basin. OMIB—Osnitsk–Mikashevichi Igneous Belt. Towns are identified in Fig. 2. One degree of latitude and longitude corresponds to approximately 110 km.

Tikich, Ingul and Ingulets Rivers (Fig. 6). It appears to be strongly controlled by the deep-seated ENE-striking faults. The westernmost of these fault lines also underlies the divide between the Dniestr and southern Bug Rivers and displaces the Moho. The ESE-strike of these deep structures parallels the grain of the Moho morphology where it rises from -45 to -35 km at the axis of the Dniepr segment of the PDD rift (Fig. 6).

In addition to the above ESE-striking deep structures parallel with the (Palaeozoic) Dniepr rift segment, a signal of early ESE-striking crustal discontinuity is shown by Kolosovskaya et al. (1992a) as the approximately 400 km long and up to 100 km wide belt of fault blocks consisting of Archaean kinzigite complexes (3.6–3.0 Ga) within and along the rift's domain between Chernigov and Poltava (Fig. 1). These complexes also constitute the northern edge of the extent of the Proterozoic Ingul–Ingulets complex. Together they reinforce the impression of an ESE-striking Precambrian crustal discontinuity in the subsurface of the Dniepr–Donets segment of the PDD rift and the southern watershed of the Dniepr River Basin.

The eastern watershed of the Dniepr River Basin straddles the approximately 900 km Donetsk–Briansk Lineament between Mariupol and Briansk (Fig. 6) which is defined by Moho contours with north-northwesterly trend (Fig. 6). The lineament underlies the transition between the Dniepr–Donets Basin and the Donets Fold Belt of the PDD rift. In this area, within and just north of the PDD rift, the Donets River cuts back into the DBL from the east (Fig. 7; Kharkov loop) and further north the Seym River cuts back into it from the west (Kursk loop). The easternmost tributaries of the lower Dniepr River cut back into the lineament system to the east (Volnovakha loop).

6.2. Tributary catchments and deep structure within the Dniepr River Basin

The basin of the Dniepr River comprises seven tributary catchment regions (Figs. 2 and 6). In the northwest, the upper Dniepr River, the Berezina and part of the Pripyat systems drain the OMIB. To the south of these and roughly symmetrical with respect to the main course of the middle Dniepr between Orsha and Kiev are the Sotch, the Seym and the lower Dniepr catchments, east of the middle Dniepr, and the larger, southern part of the Pripyat, and the Teterev and Ros catchments, west of the middle Dniepr. The divides between these tributary catchments reflect a segmentation of the Dniepr River Basin which is underpinned by deep-reaching ENE-striking discontinuities in the Precambrian complexes (Fig. 6). The deep vertical extent of these discontinuities is, locally, suggested by vertical displacement of the Moho along them (Fig. 4). Together these highlight a division of the upper and middle parts of the Dniepr River Basin in ENE-striking segments, in which the tributaries run in roughly east-northeasterly and west-southwesterly courses towards the main Dniepr. West of the Dniepr River, however, an E-striking drainage trend dominates with the main Pripyat River. The latter trend corresponds with numerous E-striking fault lines within and along the Pripyat Trough of the PDD rift and easterly striking contours on the Moho (Figs. 4, 6 and 7).

East of the middle Dniepr, at the latitude of Chernigov and Sumy, a transition is noted from the above ENE-preferred strike of stream and underlying fault segments to a narrow belt of E-striking upper branches of four of these five tributaries. The very prominent E-strike of the upper reaches of these streams and of the Oker and Seym Rivers immediately to the north, concurs with that of a number of E-striking faults shown by Kolosovskaya et al. (1992a) to the north of and *within* the PDD domain (Fig. 7). The narrow, ca. 60 km width of this Chernigov–Sumy belt of east–west stream courses, together with the ca. 400 km extent of the fault traces eastward across the DBL, define this belt as a structural corridor or lineament in its own right. It extends westward to the E-striking fault traces in the Pripyat catchment.

Within the lower Dniepr catchment area, there are five tributaries which discharge in south-southwesterly direction, *across the PDD rift*, to the Dniepr River between Kiev and Dniepropetrovsk. The river courses are conspicuously parallel with the four NNE-striking transcrustal lineaments east of Krivoi Rog (Fig. 6).

6.3. Catchments in the western part of the Ukrainian Shield

In the region south of the PDD rift, E-oriented river courses as in the upper branches of the lower Dniepr and the Pripyat systems are dominant, both within the Dniepr River Basin and to the south of it in tributaries of the middle and upper southern Bug drainage between Pervomaisk and Vinnitsa. These concur in strike with E-striking faults, Moho segments and, importantly, the ca. 200 km long narrow belt in the westernmost part of the Ukrainian Shield (Kolosovskaya et al., 1992a), at the latitude of Kirovograd with the transition from the enderbite-dominated complex, with dominantly Archaean ages (3.6–2.8 Ga) to the south and the charnockite complex with dominantly Palaeoproterozoic ages (2.4–1.9 Ga) to the north (Fig. 1). This belt coincides with an E-striking narrow belt of magnetic lows (Simonenko and Pashkevitch, 1990).

6.4. Catchments in the eastern part of the Ukrainian Shield and the Voronezh Massif

East of the DBL, surface runoff is generally eastward to the Don River and via the Oka catchment in the northeastern part of the region to the upper Volga. Near-surface lithological complexes and fault traces have a more distinct control on the stream courses than in the region west of the DBL because of the high frequency in lithological contrasts between greenstone complexes and felsic gneisses which express the southeasterly striking structural grain of the region. The Donets River has its upper reaches within the DBL and even west of this structure (Kharkov loop; Fig. 7). East of the lineament, the main Donets River follows the northern margin of the Donbas Fold Belt and meets the Don River about 100 km east of Rostov.

7. Discussion

Whereas the Precambrian basement complexes are hardly defined by Landsat spectral signatures, the current drainage systems appear to reflect a framework of deep-reaching dislocations of at least Proterozoic age. This expression is shown by both higher- and lower-order segments of the main rivers and tributaries and the watersheds, confirmed by deep geophysical observation and interpretation (Chekunov et al., 1992a) which defines these steeply dipping discontinuities as transcrustal dislocations affecting the Moho.

Local modifications of the Moho model of Chekunov et al. (1992a) by Stephenson et al. (1993, 2001), Kutas and Pashkevitch (2000), Yegorova et al. (2004) and Bogdanova et al. (2004) constitute refinements rather than radical changes. Differences in Moho contour pattern across the Donets–Briansk Lineament, together with substantial differences in the near-surface Precambrian complexes (Kolosovskaya et al., 1992a; Shchipansky and Bogdanova, 1996), highlight this dislocation as a fundamental feature in the architecture of the craton – commensurate with its present morphological expression – which has not been acknowledged to date. Other major discontinuities, like the Talnov Suture and the Kirovograd Thrust, are moderately to steeply dipping crustal-scale structures that only locally displace the Moho and have little or no expression in the drainage pattern.

The geology of the southern watershed of the Dniepr River basin is dominated by the Pripyat–Dniepr–Donets rift. Wilson (1993) notes the general tendency for intra-continental rifts to follow weak zones in the lithosphere. However, in terms of Precambrian geology the location of the rift is enigmatic because the grain of the underlying Precambrian complexes has northerly strike. The contour pattern of the Moho associated with the rift may be only of Late Devonian age with the onset of uplift of the basement in the mid-Frasnian (Wilson and Lyashkevitch, 1996). On the other hand, the distribution of lithological complexes west of the Krivoi Rog Suture Zone (Kolosovskaya et al., 1992a) does suggest a Precambrian crustal discontinuity parallel with the rift with large units of Archaean kinzigite complexes along the northern edge of the Proterozoic Ingul–Ingulets complex. The present location of the Dniepr River to the south of the rift may point to post-Devonian deformation as for instance during the inferred kilometer-scale uplift of the southern shoulder of the rift during the Early Permian (Stovba and Stephenson, 1999; Stephenson et al., 2001).

From the multitude of consistent spatial coincidence between deep-reaching, instead of shallow, geological discontinuities and elements of the current drainage network, we postulate a deep-seated structural framework despite the sedimentary cover and farmlands. In view of the locally inferred inception ages and the present morphological expression we arrive at a working hypothesis of long-lasting probably punctuated reactivation of transcrustal dislocations dating back to at least the Early Proterozoic. This is corroborated by regional re-levelling observations reported by Mescheryakov (1959) and his conclusion that ancient structures of the Russian platform are still active.

The boundaries between the here defined Moho domains may represent lithosphere-scale sutures that are, however, variably expressed in the near-surface geology. In the eastern part of the region, the Donetsk–Briansk Lineament and the Krivoi Rog Suture Zone are clearly visible because of distinctive structural and lithological contrasts across them. In the western part of the Ukrainian Shield the presently studied maps do not provide information to decisively link for instance the boundaries of the Kirovograd–Pripyat Moho domain to corresponding discontinuities in shallow basement complexes. This is probably due to steeply to moderately dipping thrust complexes in the marginal zones of the Kirovograd orogen (Galetsky and Pastukhov, 1993).

The ENE and E–W orientations of the Moho grain of the Osnitsk–Mikashevichi and the Kirovograd–Pripyat domains, respectively, are reflected in the pervasive fabrics of corresponding surface fault traces and drainage elements outside these domains proper (Figs. 6 and 7, respectively). While the processes responsible for the evolution of the ca. 2.0 Ga OMIB could have affected a much broader belt within the then basement to the present south, a relation between the E-striking elements visible in the above Kirovograd–Pripyat Moho domain *s.s.* and the co-linear fabric of near-surface fault traces and drainage elements far beyond this domain is at present very puzzling. Despite the absence of distinct Precambrian lithological elements along this strike the extensive development of this fabric across all six major domains suggests a sub-crustal source. Its eastern extent corresponds closely to the Kharkov and Volnovakha loops in the eastern watershed of the Dniepr River Basin where higher densities of E-striking fault traces suggest structural corridors in support of the "metallogenic mega-zones of activation" (Kolosovskaya et al., 1992b).

The known iron and gold districts along the Krivoi Rog Suture Zone, the Kirovograd Thrust and the Talnov Suture, and in the Voronezh Massif appear unequivocally hosted by steep transcrustal discontinuities and by crustal-scale thrust belts. Wherever complexes of banded iron formation are part of the host rock association, highly variable magnetization is inferred to witness high-temperature fluid–rock interaction. As in the case of the probably Proterozoic formation of magnetite in these complexes, the same or similar fluid–rock interaction and deformation may have upgraded Archaean (prot)ores of gold and base metals in the underlying greenstone complexes. Together these identify the transcrustal structures as prominent channels for fluid transport, most probably also beyond the extent of banded iron formation complexes as is manifested in the Kirovograd Thrust and the Talnov Suture. The latter system cuts obliquely across the Odessa and Kirovograd–Pripyat Moho domains. Along its central section, near Pervomaisk, it is accompanied by an association of highly varied lithologies, possibly even including carbonatite, and equally varied ore deposits. This exhumed lower to middle crust association overlies a disrupted and structurally heterogeneous Moho. In view of the transcurrent component of the Talnov Suture the highly oblique central segment could represent a crustal-scale releasing bend. The setting appears unique in the Sarmatian Segment.

8. Conclusions

- The Precambrian complexes and the Palaeozoic Pripyat–Dniepr–Donets rift in the southwestern part of the East European Platform are largely covered by a practically continuous patchwork of farmlands on Mesozoic and Cenozoic sediments and soils of variable thickness. Landsat and Shuttle Radar Topograhic Mission imagery only very locally allows recognition of near-surface geological configurations. Consequently, their use in the appreciation and evaluation of the published maps of the Precambrian complexes is severely impeded.
- However, drainage systems within and around the basin of the Dniepr River can be traced that appear to relate to structural features in the deep crust and the upper mantle previously inferred from deep geophysical surveys. The conspicuous spatial coincidence of numerous elements of the current drainage patterns with steep transcrustal discontinuities compellingly reinforces the inferences concerning the dislocations in the deep crust and the upper mantle. The inception ages of these discontinuities are inferred to range between the Archaean and the Middle Proterozoic. Their kinematics and dynamics remain largely unsolved.
- High-temperature hydrothermal iron enrichment in banded iron formation caused the formation of magnetite-bearing protore assemblages along the Krivoi Rog Suture Zone in the central Ukrainian Shield and along the thrust belts in the Voronezh Massif. Irregularly distributed magnetite is viewed as the cause of previously observed strong variable magnetization in elongate domains along these structures. These domains then reflect fluid–rock interaction and establish the structures as prominent deep-reaching fluid conducts that also account for the hydrothermal gold deposits in these domains. The above mineralized districts locate within and close to the E-striking Chernigov–Sumy and Pervomaisk-Dniepropetrovsk structural corridors. The significance of their intersection with the Krivoi Rog Suture Zone and the thrust belts in the Voronezh Massif as domains of episodically increased permeability should not be precluded.
- In the southwestern part of the East European Platform, Moho morphology defines transcrustal dislocations. The magnitude of these structures, both vertically and laterally, establishes them as deep-seated pathways for heat, fluids and mantle-sourced magmas involved in the evolution of mineral deposits, proportionate with the world-class iron ore

deposits along them. The longevity of the transcrustal dislocation framework till the present day, inferred from the current drainage systems, is corroborated by regional re-levelling surveys. The kinematics and dynamics of this framework merit high-priority investigation.

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