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Spatial and Temporal Distribution of Gold Deposits in the Urals

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Abstract

During the past 10 years, the Paleozoic Urals mountain belt has been the subject of internationally based, deep seismic, and ancillary geologic studies aimed at improving our knowledge of the lithospheric evolution of the orogenic belt, in general, and its prominent crustal root, in particular. In view of its wide-ranging mineral endowment, especially for gold, this work also provides important keys to help clarify relationships between collisional tectonic processes and gold mineralization. Following an outline of current ideas on the tectonic evolution of the Urals, we present an overview of the distribution of the majority of known gold deposits. This information, together with the available isotopic and geologic age data of associated alteration assemblages, is compared to available geochronological data for various magmatic and deformation episodes. Spatial and temporal relationships suggest that hydrothermal mineralizing processes and the geodynamic evolution of the orogen are linked. In an attempt to analyze the deep structural framework of the orogen, down to the mantle, we have also examined a number of subcontinental- and regional-scale continuous geophysical datasets.

The Urals have been subdivided traditionally into a series of north-south–striking tectonic zones but more recently into three principal tectono-magmatic sectors, which comprise a Suture sector along the Main Uralian fault zone and two sectors with tectonically imbricated island-arc, transitional (viewed as active continental margin), and continental zones. Gold deposits are found in all tectono-magmatic sectors of the orogen. Minor gold occurs in Siluro-Devonian volcanic-hosted massive sulfide deposits, magnetite(-copper) skarns, and porphyry copper deposits. In a number of cases, younger structures (shear zones, faults, and their intersections) have controlled the deposition of higher gold grades. In the Urals, this has led to the concept of progressive concentration of gold during later tectonic overprinting, and the understanding that regional deformation and hydrothermal fluid-rock interaction in the Late Carboniferous to Early Triassic upgraded gold contents of earlier deposits. During the Late Carboniferous to Early Triassic, gold-bearing quartz vein lodes, which effectively encompass the majority of the larger gold deposits in the Urals, were also formed in structural-chemical traps. Some deposits, such as Mindyak that is hosted by tectonic mélanges along the Main Uralian fault zone, are clearly typical late-orogenic lode gold deposits. Others occur within and along the margins of early to middle Carboniferous older granite and, although local orthomagmatic relationships have been described, most recent observations now favor a strong structural control on the lodes and no direct genetic association with granite intrusion. In the two largest gold deposits, Kochkar and Berezovskoe, gold mineralization was controlled by structural and combined structural-chemical traps in dilational jogs in both shear and contact zones. Locally, gold mineralization has been shown to occur during a change from orthogonal to transpressional compression.

The inferred ages of the lode gold deposits suggest they are mostly coeval with the generally undeformed Permian-Early Triassic younger granites. However, a spatial relationship with gold mineralization has not been observed. The younger granites were formed in an extensional regime following Ural-wide magma generation, caused by a thermal flux attributed to underplating of the crust by mantle-derived mafic magmas. The widespread distribution of this late thermal event, during changes in stress regime, and the involvement of magma-generating mantle processes suggest regional delamination in the lithosphere and concomitant upwelling of the asthenosphere. These processes may have largely occurred prior to the formation of the prominent crustal root of the Urals, which formed during subsequent transpressional convergence. Another, Triassic, Ural-wide phase of hydrothermal alteration has been recognized, but associated gold deposits have been documented in only two cases. We tentatively attribute this phase to destabilization of the lithosphere of the wider Altaids, reflected by the formation of the West Siberian and Central Asian basins, east of the Urals, during the Mesozoic.

The integrated analysis of magnetic, Bouguer gravity, heat flow, and crustal thickness data suggests that a major indenter of the East European craton is responsible for a singular, transcrustal, sidewall ramp in the subsurface of the middle Urals. This ramp may extend into the mantle and formed the principal conduit zone for mineralizing fluids. The world-class Kochkar and Berezovskoe gold deposits are adjacent to this proposed conduit.

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Introduction

THE URALS are often viewed as a north-south intercontinental orogenic belt between Europe and Asia. This belt extends from the Aral Sea in the south to the Barents and Kara Seas in the north, a distance of approximately 2,500 km (Fig. 1). However, the belt can also be viewed as the western portion of the ~3,000-km-wide Uralides (Hamilton, 1970), or the Altaid collage (Sengör et al., 1993; Sengör and Natal'in, 1996a, b), or the Central Asian mobile belt (Kröner et al., 1998) between the East European and the Angara cratons. This region consists predominantly of Paleozoic to early Mesozoic sedimentary, volcano-sedimentary, and plutonic complexes, with fragments of Precambrian continental and oceanic crust. The Urals mountain belt is characterized by a prominent crustal root (Juhlin et al., 1995; Thouvenot et al., 1995; Berzin et al., 1996; Carbonell et al., 1996; Echtler et al., 1996; Knapp et al., 1996), in contrast to the other late Paleozoic orogenic belts in Europe, and by very low heat-flow density (Kukkonen et al., 1997).

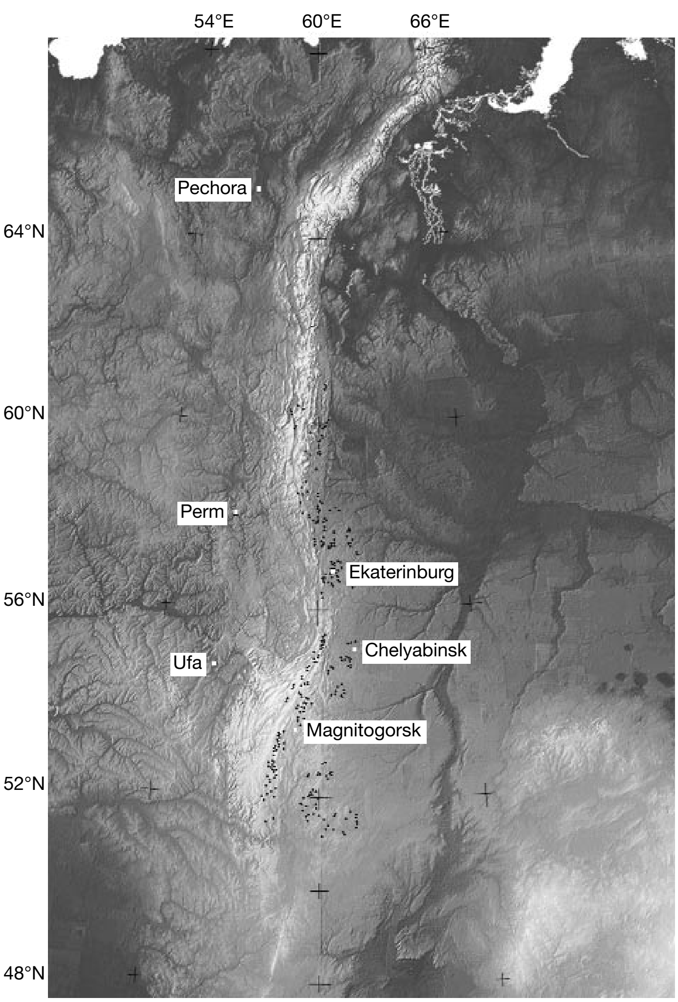


FIG. 1. Location and topography of the Urals conform to the GTOPO30 model (U.S. Geological Survey, 1998). The mountainous part corresponds to the Urals west of the Main Uralian fault zone. The eastern part has very subdued relief. Gold deposits are shown as dots, corresponding to Figure 4. The distance between Ufa and Magnitogorsk is ca. 250 km.

During the past 10 years, several projects aimed at improving our knowledge of the lithosphere of the Urals have been conducted as joint enterprises by research teams from Russia, Western Europe, and North America within the framework of the EUROPROBE program of the European Science Foundation (e.g., Berzin et al., 1996; Carbonell et al., 1996; Echtler et al., 1996, 1997; Gee and Zeyen, 1996; Knapp et al., 1996, 1998; Brown et al., 1998; Steer et al., 1998). This work has produced a comprehensive overview of the orogenic belt that provides important keys to help clarify the relationships between collisional tectonic processes and mineralization. This paper focuses on the gold deposits of this well-endowed region (Koroteev et al., 1997).

First, we outline current ideas on the evolution of the Urals, followed by a review of the distribution of the majority of the gold deposits known to us. We have compiled the available isotopic and geologic age data for alteration assemblages preceding and associated with gold deposition. We compare these to other geochronological observations on magmatic and deformation episodes. Spatial and temporal relationships tend to suggest that the hydrothermal mineralizing processes and the geodynamic evolution of the orogen are linked. In these related processes, delamination in the lithosphere, during changes in stress regime, may have played an important role. The analysis of subcontinental- and regional-scale magnetic, Bouguer gravity and heat-flow datasets, in conjunction with observations on the crustal thickness of the Urals, suggests that transverse, deep-penetrating fault zones in the middle Urals have been effective in focusing on gold-bearing hydrothermal fluids.

Outline of the Evolution of the Urals

Ural-Altaid relationships

Substantial advancements in the understanding of the geologic evolution of the Urals resulted from the work of Hamilton (1970), Zonenshain et al. (1984, 1990), Sengör et al. (1993), and Sengör and Natal'in (1996a, b), who viewed the evolution of the Urals in the framework of the Altaids of Central Asia, between the European and Angara cratons (Fig. 2). Principal elements comprise: (1) the breaking up of a Precambrian supercontinent into the East European and Angara cratons during the Late Proterozoic and early Paleozoic, following a collisional event that can presently be traced in the so-called Pre-Uralide and Baykalide belts; (2) the evolution of a Kipchak arc subduction complex and a Khanti-Mansi Ocean; and (3) the development of east- and west-verging subduction zones along the eastern edges of the East European craton, starting in the Middle Ordovician. The bivergent nature of the Urals also emerges clearly from deep seismic profiles (Berzin et al., 1996; Echtler et al., 1996).

Tectonic zonation in the Urals

On the basis of studies in the southern Urals, the belt is traditionally divided into six tectonic zones. From west to east these are the Pre-Uralian foredeep and the West Uralian, the Central Uralian, the Magnitogorsk-Tagil, the East Uralian, and the Trans-Uralian zones (Fig. 3A). These fall into two

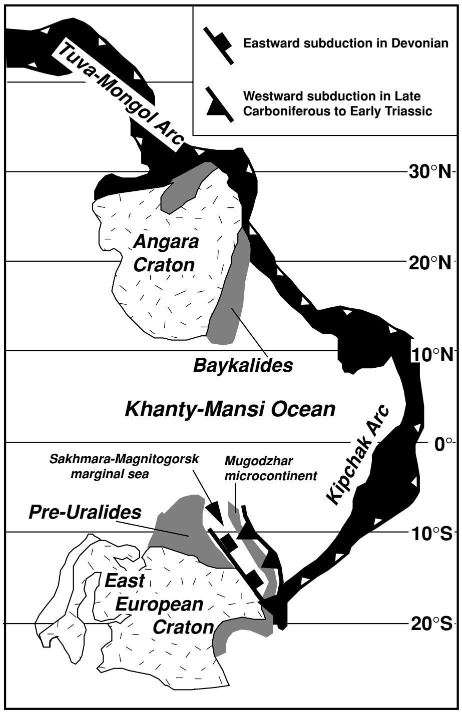


FIG. 2. Spatial relationships between the East European and Angara cratons in the Late Ordovician (after Sengör and Natal'in, 1996a), with westward Devonian and eastward Late Carboniferous-Early Triassic subduction in the Urals (Brown et al., 1998).

main areas separated by the Main Uralian fault zone, which is seen as the principal Suture zone and can be recognized along most of the length of the Urals belt. The three western zones comprise remnants of Late Proterozoic to early Paleozoic intracontinental rifts (Maslov et al., 1997) within a Paleozoic foreland thrust and fold belt (Pérez-Estaún et al., 1997), together with Devonian complexes of high-pressure metamorphic facies rocks (Table 1; Matte, 1995; Brown et al., 1998). To the east of the Main Uralian fault zone there are complexes that evolved along oceanic spreading ridges and in island arcs. These are preserved in the largely Devonian Magnitogorsk zone in the south and the largely Silurian Tagil zone to the north. Yazeva and Bochkarev (1996) have argued that the Tagil zone extends much farther south than had previously been thought (Fig. 3B). The East Uralian zone comprises metamorphosed Precambrian basement, including the Mugodzhar and Saldinsk microcontinents (Fig. 3B), intruded by voluminous Late Carboniferous and Permian granites (Table 1; Bea et al., 1997; Fershtater et al., 1997). To the east, this zone is in tectonic juxtaposition with the Trans-Uralian zone also comprising further remnants of Silurian and Devonian island arcs, oceanic crust, and metamorphosed deepwater sediments (Hamilton, 1970; Zonenshain et al., 1984, 1990; Sengör et al., 1993). In the course of middle to late Paleozoic collision these complexes were stacked and amalgamated into an approximately 200-km-wide belt. Deformation has led to strongly variable dissection, imbrication, and superposition of the principal tectonic zones.

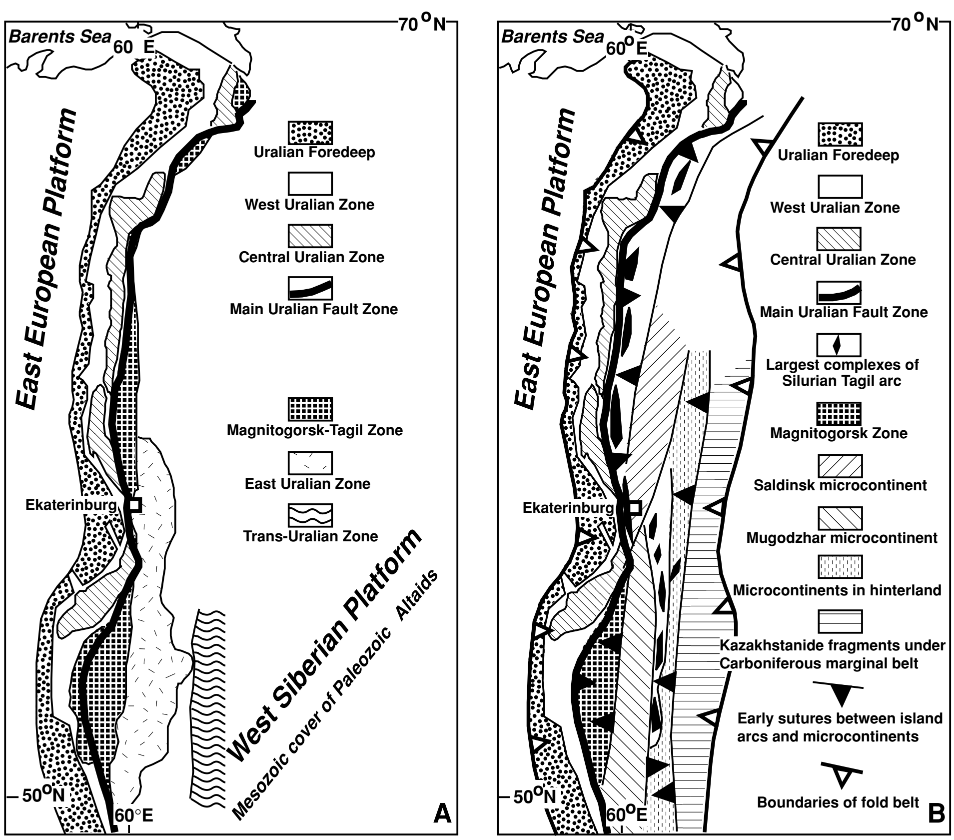
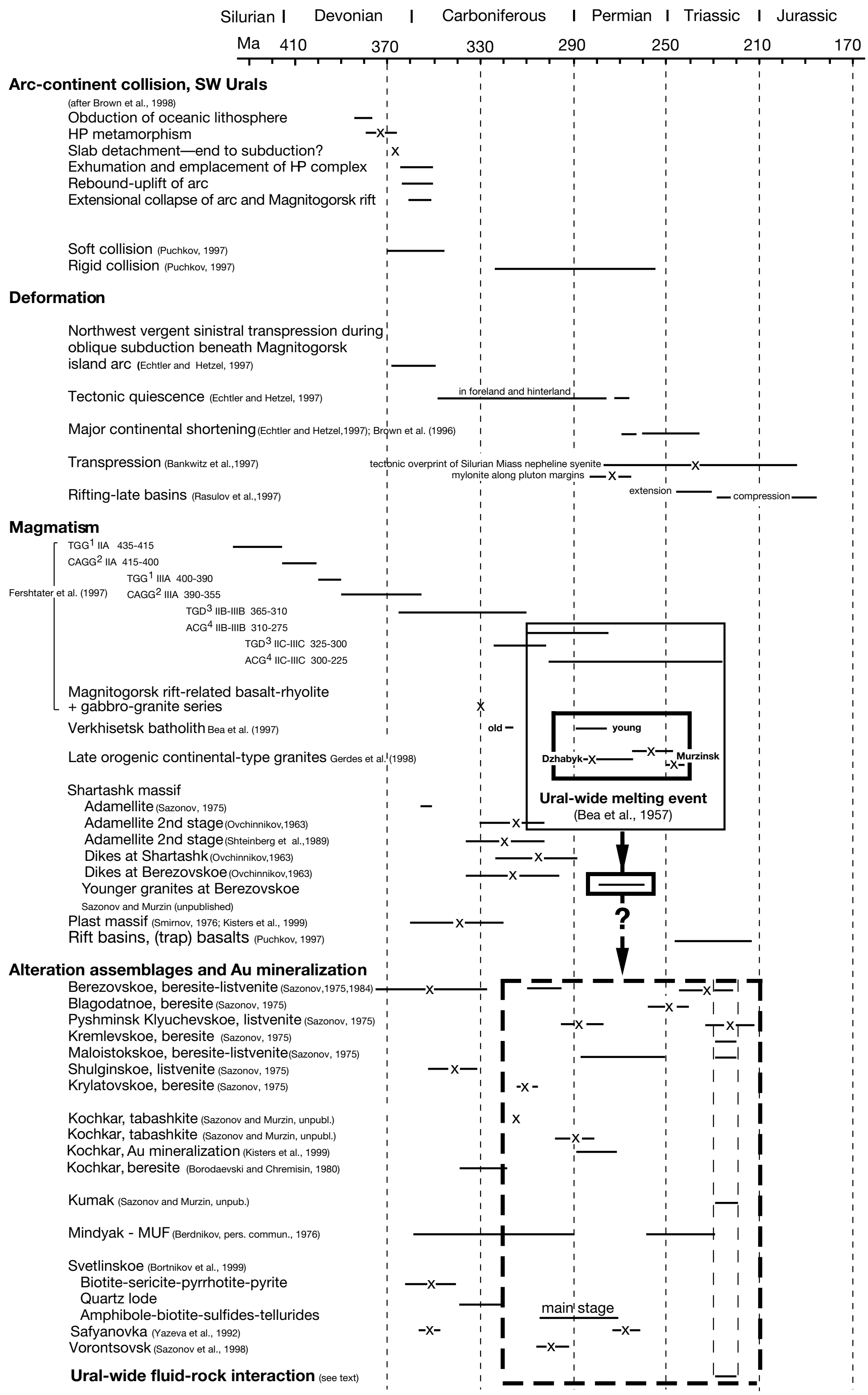


FIG. 3. A. Traditional tectonic zones of the Urals (after Puchkov, 1997). B. Southward extent of the Silurian Tagil arc (after Yazeva and Bochkarev, 1996).

TABLE 1. Chronology of Principal Events



[1] TGG = Tholeiitic-gabbro-granite series
[2] CAGG = calc-alkaline gabbro-granite series
[3] TGD = tonalite-granodiorite series
[4] ACG = anatectic crustal granites

Abbreviations: II = Northwest island arc-continental sector, III = Southeast island arc-continental sector, A = island arc, B = active continental margin or transitional, C = continental zones

Arc-continent collision and deformation

From the integration of deep seismic and geologic surface studies in the southern Urals, Brown et al. (1998) suggested the following principal stages in the collision of the Magnitogorsk island arc with the East European craton (Table 1): (1) westward obduction of oceanic crust and eastward subduction of part of the fore-arc block, in the Middle Devonian; (2) high-pressure metamorphism when attenuated continental crust entered the subduction zone, in the Givetian and Frasnian; (3) uplift and erosion of the volcanic arc, folding and syntectonic sedimentation in the fore-arc region, exhumation of high-pressure rocks, and possible slab break-off, toward the end of the Frasnian; (4) increased erosion of the volcanic arc, waning of volcanism, continued westward thrusting of the accretionary complex over the continental margin, and buoyancy-driven exhumation of high-pressure rocks, during the Famennian to Early Tournaisian; (5) extensional collapse (see Dewey, 1988, and Ménard and Molnar, 1988, for discussion of collapse processes) of the volcanic arc and deposition of carbonates on top, emplacement of high-pressure rocks, and continued buoyancy-driven uplift and exhumation of the margin of the East European craton, during the Tournaisian; and (6) development of the foreland thrust and fold belt and doming of the accretionary complex along the western margins of the Urals and westward subduction of continental crust, with associated plutonic and volcanic activity and deformation along the eastern margins of the Urals, between the Early Carboniferous and Early Triassic.

Puchkov (1997) advocates that Paleozoic collision in the Urals began in the middle Late Devonian but with only slight thickening of the crust during thrust stacking (Table 1). A second collision, dated as mid-Carboniferous to Late Permian (Table 1), resulted in development of a mountain range with a deep crustal root, generation of the anatectic granites in the East Uralian zone, and formation of the Pre-Uralian foredeep and intermontane basins. Puchkov (1997) concurs with Brown et al. (1998) in recording local tensional structures developing in the Visean to Namurian, immediately preceding the second collisonal event, with reference to a rift structure in the Magnitogorsk zone (Fig. 4). In this rift, extensive shelf carbonates developed along with mantle-derived plutonic and volcanic complexes during the early to middle Carboniferous (Table 1).

From detailed studies in the southern Urals, Bankwitz et al. (1997) suggested shortening of the Uralian crust by bivergent stacking and obduction of oceanic crust along low-angle shear zones accompanied by folding along subhorizontal axes. In the Carboniferous, further crustal shortening took place along steep north-northeast–south-southwest sinistral transcurrent shears, with folds along steep axes, and may have lasted until the Middle Triassic (Table 1). These shear zones attain widths up to 20 km and are seen to affect the margins of syntectonically emplaced granitic plutons and batholiths. Bankwitz et al. (1997) attribute the transcurrent shears to escape tectonics.

The late Paleozoic deformation in the Urals reflected the relative movements of the East European and Angara cratons. However, these cratons are still separated by a wide belt containing predominantly basalt, chert, and turbidite with intervening fragments, or microcontinents, of crystalline continental crust. This led Sengör and Natal'in (1996a) to define the Altaids as a Turkic-type orogen in which collision of the principal continents did not materialize. Although Bankwitz et al. (1997) invoke escape tectonism as a major mechanism of deformation in the Urals, the principal continents themselves are thus still widely separated. Therefore, the escape deformation refers, in our opinion, more simply to the transpressive collision of the East European craton with variably sized fragments of crystalline crust. These fragments may in part have been separated from the latter craton during the Late Proterozoic to early Paleozoic or have an origin to the east. Deformation and associated sedimentary facies shifted diachronously from south to north in the course of the Late Devonian to Early Permian (e.g., Puchkov, 1997).

Tectono-magmatic zonation in the Urals

Fershtater et al. (1997) distinguish three principal tectono-magmatic zones in the Urals (Fig. 4). These are the Suture sector along the Main Uralian fault zone, together with the tectonically imbricated Northwest and Southeast island arc-continental sectors, which are delimited by north-northeasterly trending major shear zones. The Suture sector is marked by mafic-ultramafic complexes of Middle Ordovician to Early Devonian age. Such complexes are also found in the central and eastern areas of the Urals. Most of these (e.g., along the Serov-Mauk and Alapaevsk faults; Fig. 4) consist of harzburgite, gabbro, and basalt and reflect oceanic domains.

The Northwest and Southeast island arc-continental sectors are each formed of an island-arc zone, a transitional zone (viewed as active continental margin), and a continental zone (Fig. 4). The Siluro-Devonian island-arc zones are built up of basalt-rhyolite and basalt-trachyte series and tholeiitic gabbro-granite series and subsequent calc-alkaline gabbro-granite series. Here, tonalite-granodiorite series and anatectic crustal granites developed during the Late Devonian to Early Permian (Table 1; Fershtater et al., 1997). In the continental zones such complexes were emplaced during the middle Carboniferous to Late Permian (Table 1). The general age relationships, therefore, suggest independent magmatic evolution of the Tagil and Magnitogorsk island arcs during the Siluro-Devonian and tectonic amalgamation, followed by a largely common magmatic evolution during the Late Devonian to Late Permian (Table 1). The two-fold division into island arc-continental sectors appears to be reflected by corresponding differences in the Suture sector, which, along the Northwest island arc-continental sector, embraces the so-called platinum-bearing belt (Savelieva and Saveliev, 1992; Garuti et al., 1997; Fig. 4).

Fershtater et al. (1997) found that the Middle to Late Ordovician oceanic-type magmatism, preserved in the Suture sector and along large oblique southwest-northeast shear zones farther east (Fig. 4), is characterized by eastward impoverishment in incompatible elements such as Th, Sr, and La. In the island arcs, magmatism evolved from low K tholeiitic in the west to high K calc-alkaline rocks in the east. In the tonalite-granodiorite batholiths of the transitional zones, an eastward increase of incompatible Rb and Th is observed. Despite many similarities between the magmatic evolution of the Northwest and Southeast island arc-continental sectors, differences in

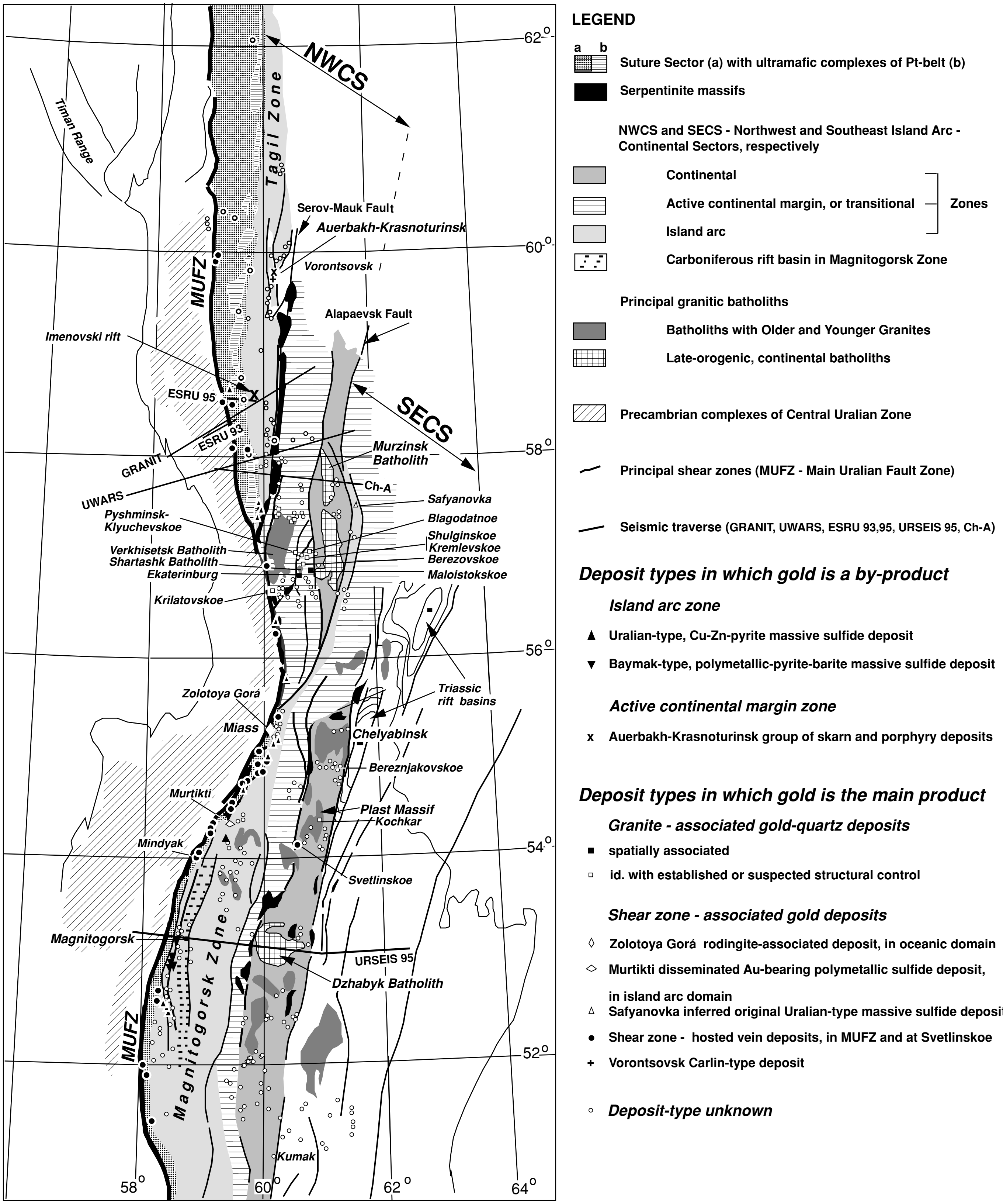


FIG. 4. Gold deposits in relationship to the tectono-magmatic zones of Fershtater et al. (1997) and locations of deep seismic traverses. Location of Imenovski rift after Knapp et al. (1998).

geodynamic regimes are suggested. For example, the Carboniferous batholiths in the north have adakite-like chemistry and asymmetrical zonation, while in the south such batholiths do not have adakite-like chemistry, are unzoned or concentrically zoned, and are richer in incompatible elements (Bea et al., 1997; Fershtater et al., 1997). Also, reported $^{87}Sr/^{86}Sr_{initial}$ ratios show a different behavior with, for instance, higher values in the northern Murzinsk batholith (0.7120) and lower values (0.7045) in the southern Dzhabyk batholith (for locations, see Fig. 4). The whole-rock chemistry of these batholiths is very similar and suggests derivation by anatexis from crustal protoliths. However, the low values of $^{87}Sr/^{86}Sr_{initial}$ ratios at Dzhabyk suggest involvement of oceanic crustal materials.

From investigations in the Verkhisetsk batholith, in the west (Fig. 4), Bushliakov and Sobolev (1976) showed the existence of older and younger granites (Table 1). Bea et al. (1997) indicated the older granites (~315–320 Ma) were generated by partial melting of metabasalts at temperatures of ~1,000°C and pressures of ~12 kbars. The thermal regime points to subduction of a young lithosphere and a protolith of subducted oceanic crust is favored. The older granitic rocks are intruded by a core of younger, fine-grained, undeformed granitoids (~275–285 Ma) comprising granodiorites, adamellites, and granites with abundant dike swarms of leucogranite, aplite, and pegmatite. These were produced by anatexis of the older granitic rocks. The abundance of dikes and the undeformed fabric of the younger granites indicate that they were generated and emplaced during an episode of extension or noncompression. These equilibrated at pressures around 4 kbars (Bea et al., 1997).

Bea et al. (1997) have shown that the younger granites are extraordinarily abundant throughout the Urals, comprising most of the large batholiths in the east and the younger massifs in the west. These were most likely formed by remelting of older granitoids, as in the case of the Verkhisetsk batholith. To explain this younger Permian-Early Triassic melting event (Table 1), Bea et al. (1997) suggest a thermal input from the mantle associated with underplating of the crust by mafic magmas.

Late- to post-orogenic history

During the early Mesozoic, after the transpressional deformation, north-northeast–south-southwest-trending graben structures developed within and along the Urals and in northwest Siberia (Rasulov et al., 1997; Fig. 4). The graben fills of basaltic effusions and continental sediments were folded during the Late Triassic to Early Jurassic (Table 1). On the basis of deep seismic reflection work along the ESRU '93 and '95 profiles (Fig. 4), Knapp et al. (1998) interpret abrupt thinning of the crust beneath the Imenovski graben (Fig. 4) and reactivation of the Main Uralian fault zone as evidence of partial extensional collapse of the middle Urals, associated with the development of the West Siberian basin in the early Mesozoic. It is not clear if these grabens and intervening horsts can be viewed as a Basin and Range province with its implied orogenic collapse (e.g., Ménard and Molnar, 1988). However, the vast region between the East European and Angara cratons was affected by late Paleozoic to early Mesozoic extension, which resulted in the formation of the Nadym, Nurol, Junggar, Alakol, and Turfan basins farther east (Allen et al., 1995; Sengör et al., 1996a, b). In contrast, recent results of deep seismic work across the southern Urals indicate that late-orogenic extension was very restricted if it occurred at all (Brown et al., 1998; Steer et al., 1998).

As a late Paleozoic mountain belt the Urals existed only for a relatively short time (Puchkov, 1997). Between the end of the Jurassic and the late Paleogene it was completely eroded. The present topographic expression (Fig. 1) is thought to have developed only from the late Oligocene due to forces acting at the convergent margins of the Cenozoic Eurasian plate (Puchkov, 1997).

Spatial and Temporal Distribution of Gold Deposits

Gold deposits in the Urals belt are unevenly distributed. Two relatively large regions are prominent east of the Main Uralian fault zone (Fig. 4). One concentration is along the Main Uralian fault zone and the adjacent Magnitogorsk island-arc zone, south of Miass, and the other in the Northwest island arc-continental sector in the region of Ekaterinburg. In addition, there are a number of small clusters scattered along the orogen. In the Precambrian to early Paleozoic rocks west of the Main Uralian fault zone, small gold deposits are known but their exact location and geologic context are not adequately defined at this time; these are not shown in Figure 4.

The present principal hard-rock mining districts are those of Berezovskoe, near Ekaterinburg, and Kochkar, near Plast (Fig. 4). Both districts have a long mining history dating back to 1748 when exploitation started in the Berezovskoe field. The smaller Krilatovsky lode, southwest of Ekaterinburg, and placers near Miass are also still actively exploited. According to Lehmann et al. (1999), exploration and definition drilling of mineralization within a 7 × 2-km area are in progress at Bereznjakovskoe, ~40 km southeast of Chelyabinsk (Fig. 4). Exploration and evaluation at Murtikti and Vorontsovsk are also in progress. The other deposits shown in Figure 4 have been abandoned and are no longer accessible.

In individual deposits K-Ar isotope dating of associated alteration assemblages indicates several phases of gold mineralization (Table 1). The assemblages are generally known as "beresite," consisting of quartz, sericite, dolomite-ankerite, and pyrite, and "listvenite," comprising quartz, fuchsite, magnesite, and chromite (Table 2). Gold mineralization itself is often accompanied by a sericite-rich alteration assemblage, overprinting the beresite and listvenite assemblages. In the Kochkar district, the gold lodes are closely associated with mafic dikes. These have generally been altered to an assemblage of biotite, hornblende, and zoisite. This assemblage is known as "tabashkite" (Table 2).

The gold lodes and associated alteration assemblages are structurally controlled at both local and regional scales, and gold deposits in the Urals, to a large extent, can be shown to be related to deformation processes at different scales. In the case of the granite-associated gold deposits, the relationships

TABLE 2. Mineralogical Composition of Alteration Assemblage Types

Beresite	Quartz, sericite, dolomite-ankerite, pyrite
Listvenite	Quartz, fuchsite, magnesite, chromite
Tabashkite	Biotite, hornblende, zoisite

are often debatable where isotopic ages for the older granite hosts and the ore-associated alteration assemblages show substantial differences, locally on the order of tens of millions of years (Table 1). This late timing has been documented in several other gold camps by Cassidy et al. (1998), Groves et al. (1998), Goldfarb et al. (1998), and Witt and Vanderhor (1998) and discussed in terms of orthomagmatic, (syn)orogenic, and late-orogenic, structurally controlled gold deposits.

Koroteev et al. (1997) have reviewed the distribution of the principal ore deposits of the Urals in terms of environment of formation: oceanic-spreading complexes, island arcs, active continental margins, granitic complexes, and the Main Uralian fault zone. These correspond, broadly, with the elements of the tectono-magmatic zonation of Fershtater et al. (1997; Fig. 4). In several areas, convergent deformation has led to intricate imbrication and superposition of rock complexes of island-arc and/or oceanic, back-arc, active continental margin and crystalline basement origin, bringing ore deposits of different parentage in very close proximity, in part concomitantly with mineralizing hydrothermal fluid-rock interaction. In the absence of systematic detailed structural studies we present an overview of the distribution of the gold deposits in terms of first-order geologic domains (Fershtater et al., 1997; Koroteev et al., 1997) and, where possible, outline subsequent modification due to deformation and hydrothermal fluid flow.

The western zones

West of the Main Uralian fault zone, small gold deposits are known to occur in black shales and carbonates formed in Precambrian (Riphean-Vendian) rift complexes, and also associated with bimodal volcanic and granitic rocks presumably also of Precambrian age. Generally, alteration assemblages in the country rocks indicate deposition of gold and gold-bearing sulfides from late hydrothermal solutions. In the northern Urals, gold has been found in paleoplacers, though little information is available.

Oceanic domains along and east of the Main Uralian fault zone

Dunite-harzburgite complexes and tholeiitic basalts attributed to oceanic or back-arc spreading settings are tectonically interleaved with the rocks of the Tagil and Magnitogorsk zones along the Main Uralian fault zone. They also occur along shear zones farther to the east. In association with the basalts, copper-bearing massive sulfide deposits are known in the Dombarovski region (Koroteev et al., 1997). These are comparable to Cyprus-type massive sulfide deposits and are locally known as Dombarovski-type deposits. Gold grades are up to 0.4 g/t and gold is produced as a credit during copper production (Koroteev et al., 1997).

The Zolotoya Gorá deposit (Fig. 4) is hosted by dikes with rodingite-type assemblage (diopside, garnet, apatite, and magnetite) in the Ordovician ultramafic Karabash massif within the Main Uralian fault zone. Its total strike length is about 2 km, with lenses up to 600 m long and up to 7 m wide. Gold grades were on the order of 5 g/t. Temperatures of gold mineralization have been estimated at about 450°C and pressures of 2 to 2.5 kbars (Sazonov et al., 1993). The age of the mineralization is uncertain. The affinity of the rodingite assemblages within the Ordovician ultramafic complex suggests an original suboceanic environment of formation. It is not known to what extent late Paleozoic deformation and hydrothermal fluids have contributed to the mineralization. Other deposits of this type are not known in the Urals.

Siluro-Devonian island arcs

The island arcs of the Magnitogorsk and Tagil zones comprise a sequence from basalt to andesites and dacites. Associated with these are Cu-Zn-pyrite (Uralian-type) massive sulfide deposits, polymetallic-pyrite-barite (Baymak-type) massive sulfide deposits, and disseminated gold-bearing base metal (Murtikti-type) deposits (see also Koroteev et al., 1997). Estimates of the gold contents of the original deposits are on the order of 1 g/t in the Uralian type, 2 to 3 g/t in the Baymak type, and about 6 g/t in the Murtikti type. Several of the gold deposits in the Magnitogorsk and Miass regions shown in Figure 4 are in fact Uralian- and Baymak-type massive sulfide deposits (see also Koroteev et al., 1997).

The Safyanovka deposit (Fig. 4) is interpreted as an original Uralian-type massive sulfide deposit. It is located relatively far to the east, in the intensely deformed northern part of the Magnitogorsk zone (Yazeva et al., 1992). The host rocks comprise a mélange of ultramafic, gabbro, Devonian rhyolite, dacite, and tholeiitic basalt, Carboniferous limestone, and Precambrian gneiss fragments. The original massive sulfide body consists of pyrite with subordinate chalcopyrite and sphalerite, with a veinlet stockwork of pyrite and chalcopyrite. The main body is surrounded by an alteration halo in the basaltic country rocks. Crystallization temperatures of 225° to 370°C for the main body and 370° to 520°C for the stockwork veinlets were determined by Yazeva et al. (1992). Later, deformation-controlled gold polymetallic mineralization occurred along fault intersections, with development of discordant alteration halos in the country rocks of quartz-chlorite and carbonate-chlorite and local quartz-sericite-carbonate assemblages. Early Carboniferous and middle Permian K-Ar ages have been obtained (Table 1), and crystallization temperatures of the middle Permian mineralization were determined between 150° and 200°C (Yazeva et al., 1992). Locally, a later generation of sericite-carbonate is also recognized.

The Murtikti deposit (Figs. 4 and 5) is a disseminated base metal deposit with gold-bearing pyrite, sphalerite, and galena, with local quartz(-carbonate) veins. This deposit occurs within subvolcanic andesites of the Magnitogorsk zone, which intrude tholeiitic basalts hosting the nearby Uchaley massive sulfide deposit. At the deposit-scale, the Murtikti deposit is located in the northeasterly striking, up to 5-km-wide Tungatakovski shear zone. Gold reserves are estimated to be between 60 and 100 t. Late Paleozoic brittle deformation has affected the original deposit and its host rocks, with possible remobilization of the metals at lower greenschist facies conditions (Seravkin et al., 1994).

Active continental margins (transitional zones)

The transition from the island-arc domains to the continental domains is generally complex due to tectonic imbrication. Transitional zones are identified by their predominance of andesites with subordinate trachyandesites and trachybasalts and small bodies of comagmatic gabbro, diorite, and granodiorite, often

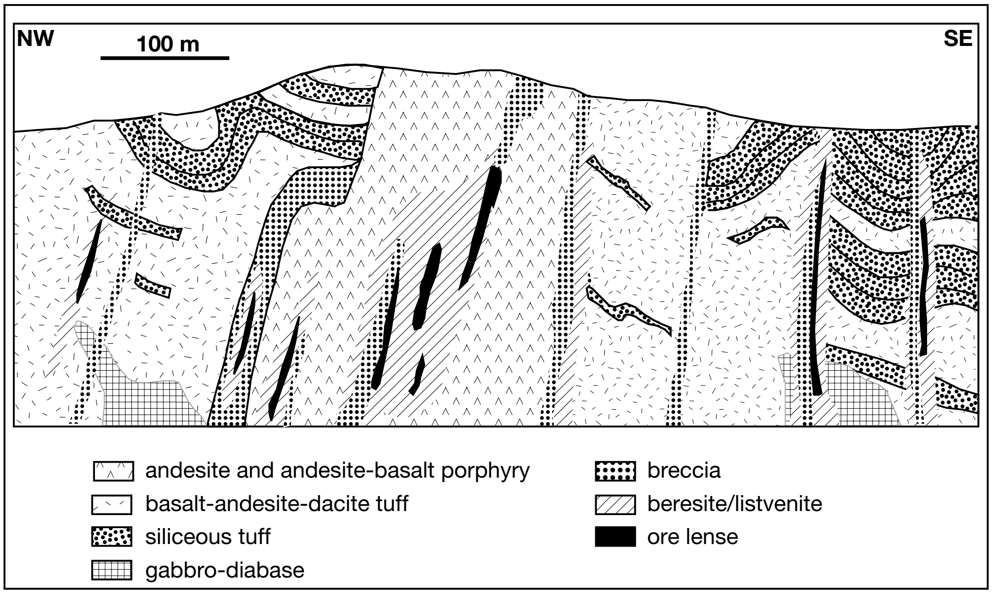


FIG. 5. Section through the Murtikti gold deposit. The ore lenses are inferred to be controlled by brittle faults within the Tungatakovski shear zone. For location, see Figure 4.

superimposed on the rocks of the island-arc domains. These sequences contain (copper-)magnetite skarns and porphyry copper deposits.

In the northern part of the middle Urals, the Devonian Auerbakh-Krasnoturinsk group of auriferous (copper-)magnetite skarns and porphyry copper deposits is located in the tectonically very complex transition between the Tagil island arc and the Precambrian Saldinsk massif to the east. Skarn mineralization of Middle Devonian age (Table 1; Sazonov et al., 1998) contains gold ranging from 0.4 to 1.5 g/t. In this district, the most prominent gold deposit is the Carboniferous Vorontsovsk deposit (Fig. 4). This deposit, however, does not appear to be a typical skarn deposit and has been compared to the Carlin-type deposits of Nevada (Sazonov et al., 1998). It is hosted by a sequence of limestones and tuffs and andesitic porphyries, which are cut by numerous subhorizontal and steep faults. Most gold mineralization occurs in quartz veins up to 200 m long and 0.5 to 1 m wide and is disseminated within an alteration halo of quartz and sericite dated at ~300 Ma (Table 1; Ogorodnikov and Sazonov, 1991; Sazonov et al., 1998) within limestones and volcanic rocks. The surface projection of the orebody measures ~1,000 × 200 m. Tonnages and grades have not yet been reported. About 20 percent of the gold is in native particles enclosed in quartz and 80 percent is within sulfides with elevated contents of arsenic, antimony, mercury, and thallium. An early sulfide assemblage is formed by pyrite and realgar and a later assemblage comprises chalcopyrite, sphalerite, galena, and sulfosalts.

Gold-bearing quartz lode deposits

The largest known gold deposits of the Urals, Kochkar and Berezovskoe (Fig. 4), are gold-bearing quartz vein deposits hosted within granitic batholiths and adjacent, often strongly deformed, volcanic and sedimentary rocks. The close spatial relationship between the gold-bearing lodes and the granitic rocks suggests that they may be genetically related. However, in detailed structural studies of the Kochkar deposit in the Early Carboniferous Plast massif (Fig. 4, Table 1), Kisters et al. (1999, 2000) found that the lodes are strongly controlled by mafic dikes that occur in a radial pattern within the granitic rocks. The dike swarm is interpreted to have been emplaced either as a result of indentation of the adjacent Borisov granite massif into the Plast massif during east-west–directed regional shortening, or during emplacement of the Borisov granite and associated doming which led to brittle fracturing of the Plast granitoids. During progressive deformation, a conjugate set of shears developed in easterly trending dikes with layer-normal dilation in the competent granitic country rocks providing access for mineralizing fluids. In this process, the sheared mafic dikes were metamorphosed to tabashkite (Table 2). Isotopic ages of alteration assemblages vary from Early Carboniferous to Early Permian (Table 1). Kisters et al. (1999, 2000) concluded that, on the regional scale, the common association of orogenic lode gold-type deposits with synkinematic granitoids in the East Uralian zone reflects the competency contrast within the supracrustal belt. Thus, these granitoids represented sites of reduced mean stress during regional deformation, focusing regional-scale fluid flow during deformation and metamorphism.

At Berezovskoe (Fig. 4), approximately 350, northerly striking, steeply dipping porphyritic granitic dikes occur in clusters in the roof of the Carboniferous-Permian Shartashk adamellite and granodiorite batholith (Shteinberg et al., 1989). The gold-bearing quartz lodes are mostly confined to these dikes and their immediate country rocks, with attitudes of 135°/>60° SW and, rarely, ~045°/30° NW. Mineralized quartz veins are also known in narrow shear zones along the contacts of the dikes. These relationships indicate a strong structural control on the lodes, well after emplacement of the

Shartashk batholith. However, chemical zonation observed in the roof of the batholith, manifested as scheelite mineralization along the contact and gold mineralization in higher levels, has been seen as an orthomagmatic association of the lodes (Bellavin et al., 1970; Chesnokov, 1973).

The gold-bearing quartz lodes are invariably preceded by wall-rock alteration comprising beresite and listvenite assemblages (Table 2), depending on the nature of the host rock. These assemblages were formed at temperatures between 410° and 150°C and pressures between 1.3 and 0.6 kbars, corresponding to depths of between 4.5 and 1.8 km (Sazonov, 1984). The available isotopic ages of beresite and listvenite alteration assemblages in the Berezovskoe district range from Early Carboniferous to Middle Triassic (Table 1).

At Blagodatnoe (Figs. 4, 6, and 7), northeast of Berezovskoe, Late Permian-Early Triassic gold- and sulfide-bearing lodes have been exploited in four mines to a depth of ~250 m. The lodes are hosted by a northeast-striking shear zone in a gabbro-peridotite massif southeast of the Kedrovski adamellite. The ore-hosting zone is about 3 km long and up to 80 m wide. It contains lenses of pyroxenite, gabbro, various granitic rock types, and actinolite-rich schists. Dikes of granite, granodiorite

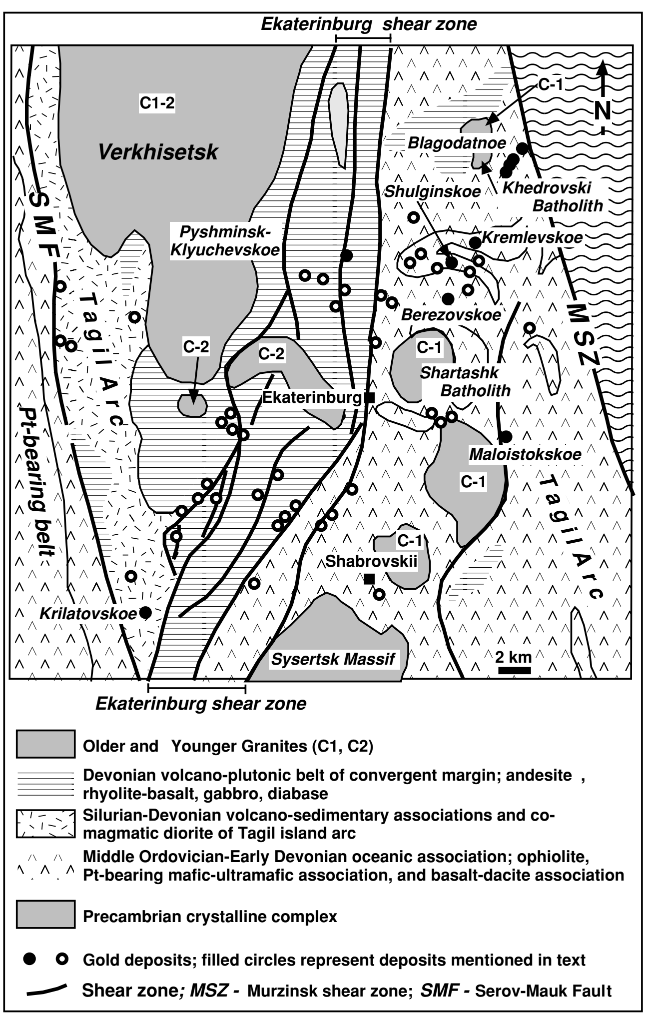


FIG. 6. Distribution of gold deposits in the Ekaterinburg region.

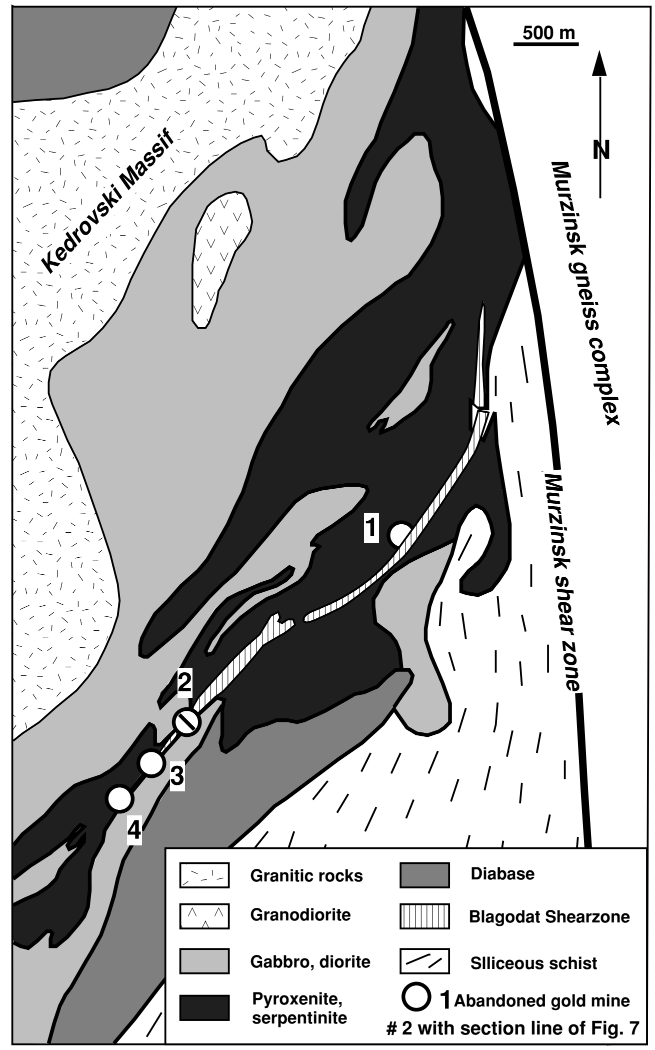


FIG. 7. Geologic sketch map of the Blagodatnoe gold lode field. For location, see Figure 4.

porphyry, and lamprophyre have been recognized, all of which predate the local schistosity. Locally, mylonites have been identified. Fluid-rock interaction is reflected by chlorite, talc-chlorite, talc-carbonate, beresite, and listvenite assemblages, locally with tourmaline and carbonates. The lodes show an en echelon distribution. We interpret the hosting structure as an *R* shear related to the Murzinsk shear zone.

The setting of the Blagodatnoe lodes (Figs. 6 and 7) and of those to the southwest of Ekaterinburg (Fig. 8) strongly points to a regional shear zone control. This is also illustrated by the concentration of gold deposits at the northern and southern tips of the Verkhisetsk batholith (Fig. 4), suggesting dilational zones may have played a role in lode emplacement.

In the tectonic mélanges of the Main Uralian fault zone several gold-bearing quartz lode deposits are known in the southern and middle Urals. Of these, the Mindyak deposit (Fig. 4), until its closure in 1998, has received the most attention. Kisters et al. (1999, 2000) documented a strong structural control on the lodes at Mindyak (Fig. 4) by faults that developed late in the kinematic history of the Main Uralian fault zone

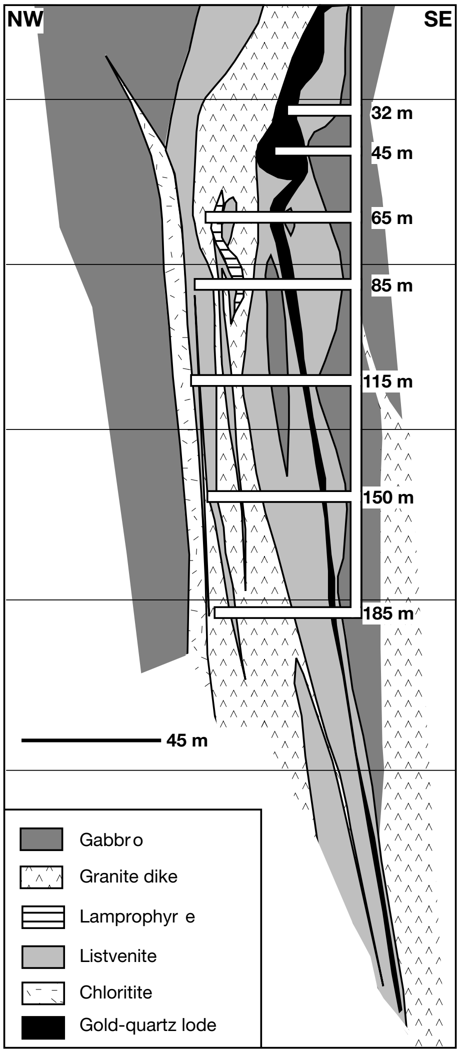


FIG. 8. Section across the Blagodatnoe shear zone in mine 2. For location, see Figure 7 (after Samartsev et al., 1973).

during reactivation of early thrusts and reverse faults, coinciding with a shift from orthogonally convergent to predominant transcurrent deformation. These form an anastomosing network defining lozenge-shaped domains characterized by the development of complex sets of third-order faults and fractures. The extent of the mineralization is determined by the size of the domains enclosed by second-order structures. At Mindyak, the strike length of the mineralization is 1.2 km with a width between 120 and 200 m. In this environment, individual structural domains produced up to 50 t Au. Here, multiple phases of mineralization can be recognized from overprinting relationships, but Kisters et al. (1999) suggest a fluid continuum within evolving fault zones rather than discrete pulses of hydrothermal activity. On the basis of K-Ar ages of micas from associated alteration assemblages, two age groups have been recognized between 360 and 290 and 260 and 230 Ma, respectively (Table 1; P.G. Berdnikov, pers. commun., 1976).

The Svetlinskoe deposit (Fig. 4) is geologically complex with a widely varied assemblage of rock types in mineralized shear zones. These include fragments of greenschist and amphibolite facies metavolcanics and metasediments, together with different types of granitic rocks. Locally, the metamorphic rocks show granitization. Three stages of mineralization have been recognized by isotopic dating of the associated alteration assemblages (Table 1; Bortnikov et al., 1999). Quartz-sericite bodies with disseminated pyrite, pyrrhotite, chalcopyrite, galena, sphalerite, and native gold formed in the Early Carboniferous, carrying an average of 0.49 g/t gold. During the second stage, in the early to middle Carboniferous, gold-bearing quartz veins with pyrite and scheelite were formed in association with beresite-listvenite assemblages. The grade of this type is 4 to 5 g/t. In the Late Carboniferous to Early Permian, the most important gold stage occurred in association with an assemblage of actinolite, biotite and pyrite, pyrrhotite, pentlandite, chalcopyrite and native gold at temperatures >400°C. The grade of this high-temperature mineralization has not been reported. Gold reserves are estimated to be 58 t (Bortnikov et al., 1999).

Timing of Mineralization, Deformation, and Spatial Relationships with the Granites

From the preceding overview, recurrent difficulties occur when trying to classify gold deposits in the Urals because of late overprinting of the primary deposits. Also there are questions whether a spatial association between granitic rocks and the orogenic quartz gold lode deposits implies a generic one

In the first case, these complexities are well illustrated for different parts of the Urals by the Murtikti and Safyanovka and possibly the Zolotaya Gorá deposits. The Vorontsovsk deposit is another case where Late Carboniferous deformation and associated fluid-rock interaction may have upgraded gold grades in the Auerbakh-Krasnoturinsk district of Devonian magnetite- and magnetite-gold-(copper)-bearing skarns. A comparable increase in gold grades is also observed at Svetlinskoe, with the main stage of mineralization in the Late Carboniferous-Early Permian. This has led to the concept in the Urals of a progressive concentration of gold during the later tectonic evolution of many deposits or, now in our view, to the hypothesis that regional deformation and hydrothermal fluid flow, which affected all tectono-magmatic zones in the Late Carboniferous to Early Triassic remobilized gold from earlier deposits. Although earlier deposits may show evidence of later structural control, we believe there is still need for a distinction of this type from deposits that are principally syn- to post-orogenic deposits localized by structural-chemical traps within shear zones, as is generally agreed in the case of the Mindyak deposit. In the second case, the conclusions of Kisters et al. (1999) on the structural control of mineralizing fluid flow in the Kochkar and Mindyak deposits can be extended to other lode deposits of the middle Urals in view of (1) the apparent local scarcity of granitic complexes in the southern part of the Ekaterinburg gold lode region (Fig. 8); (2) the shear zone control of gold lodes and alteration assemblages in the northern part of this region, as at Blagodatnoe (Figs. 6 and 7); (3) the discordant attitude of the lodes at Berezovskoe relative to the host granite porphyry dikes; and (4) the location of gold districts in probable pressure shadows at the tips of major granite batholiths, as in the case of the Verkhisetsk batholith (Fig. 4). Gold mineralization may have been dominantly a function of fluid flow, controlled by structural and combined structural-chemical traps in dilational jogs in both shear and contact zones.

Gold mineralization tends to occur within and along granitic complexes belonging to the older granites. However, the majority of the available isotopic ages of the associated alteration assemblages suggest a close temporal relationship between the mineralization and the younger granites (Table 1). On the other hand, a spatial relationship between gold mineralization and the younger granites has not been observed. Comparable ages are observed in deposits hosted by shear zones where granitic rocks are apparently absent and in deposits that were clearly modified by deformation and hydrothermal fluid flow. Consequently, a more significant genetic relationship is indicated between an important stage of gold mineralization and the Ural-wide melting event producing the younger granitoids. As suggested by Bea et al. (1997) this regional thermal event may have been due to underplating of the crust by mantle-derived mafic magmas during the Permian (Table 1). A later, Triassic, phase of hydrothermal alteration (Table 1), at the time of transtension as seen in the rift basins along the eastern edge of the East Uralian zone (Table 1), has been recognized in numerous gold districts (V.P. Vodolazskaya, S.G. Chervyakovskii, V.N. Kotov, M.B. Tarbaev, E.A. Soroka, V.N. Ogorodnikov, pers. commun., 1997). Gold deposition associated with this late phase has, however, only been documented in the Kumak district in the southern Urals and at Kremlevskoe near Berezovskoe (Fig. 4).

A number of factors constrain the formation of the gold deposits. The distribution of the Late Carboniferous to Triassic gold-bearing quartz lode districts is heterogeneous and they are found across different tectono-magmatic zones. The deposits are structurally controlled with overprinting of earlier ore deposits of different types by late fluids. The Ural-wide generation of younger granitic magmas could be linked to generation of mineralizing fluid flow in response to mafic underplating of the orogen. All these factors point to the potential role of the deep structural framework of the orogen, down to the upper mantle, in controlling the distribution of mineralization. In the following section, we examine a number of subcontinental- and regional-scale continuous geophysical datasets to address the question if, on the basis of deep-seated structural discontinuities, particular segments of the orogen were more favorable than others for mineralization.

Regional- and Subcontinental-Scale Structure and Distribution of Gold Deposits

The magnetic anomaly map (Fig. 9) shows five first-order units, which can be distinguished on the basis of different anomaly patterns. These are the East European craton, the Pechora basin, the Urals, the Altaids east of the Urals, and the Angara craton. The Urals belt is brought out by a series of long, high-amplitude anomalies with a northerly strike. In the

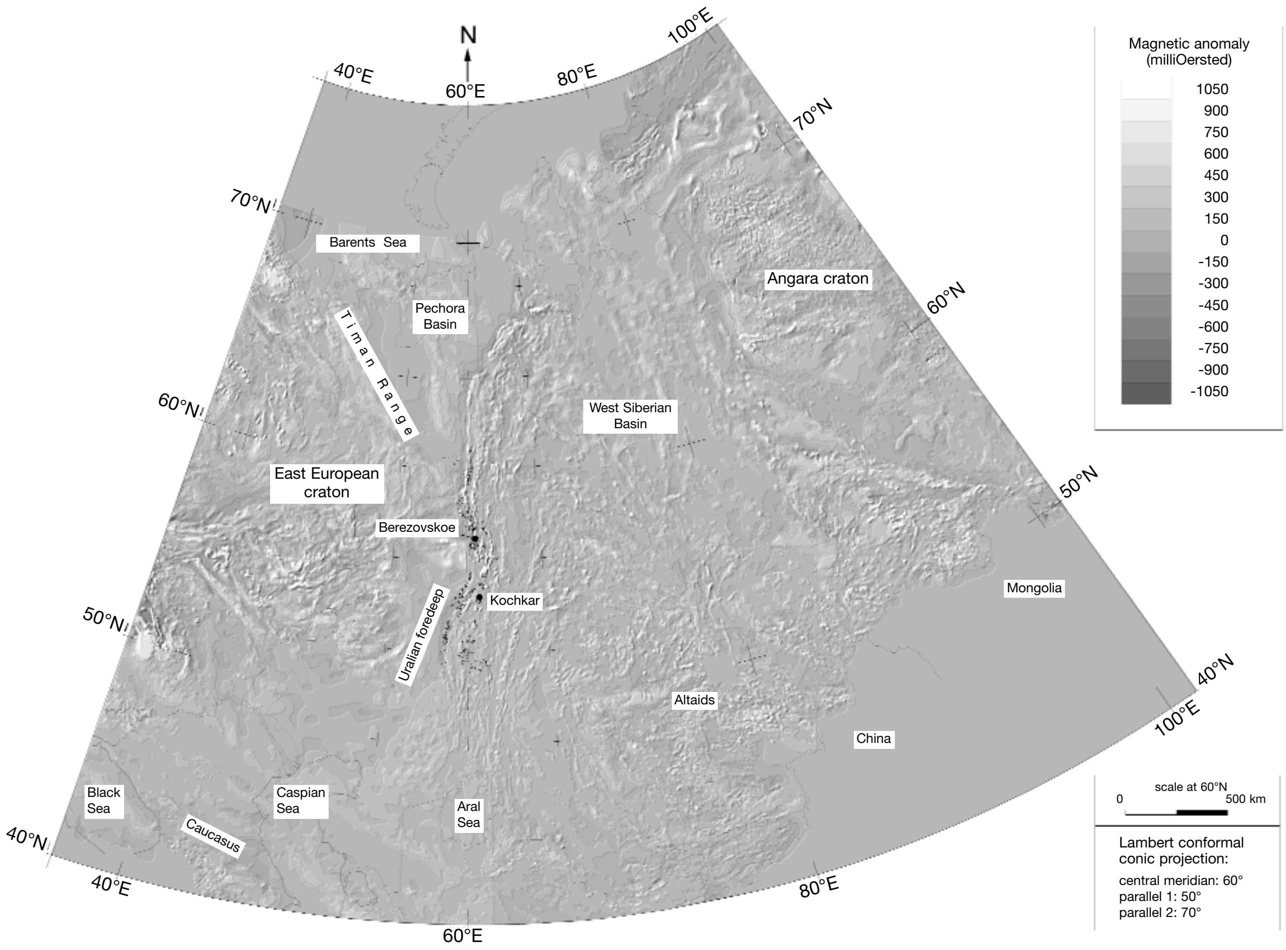


FIG. 9. Magnetic anomaly pattern of the region between the East European and Angara cratons (National Geophysical Data Center, 1996), in shaded relief illuminated from the northwest. Gold deposits are shown as dots.

middle Urals, a number of magnetic anomalies along the eastern edge of the belt stand out with north-northwest strike, at a small angle to the overall north-northeast grain, and correspond to a westward shift of the magnetic anomalies in the northern Urals relative to those in the southern Urals.

Along the URSEIS '95 traverse across the southern Urals (Fig. 4), a crustal thickness (Fig. 10) of 60 km is indicated beneath the Magnitogorsk zone (Berzin et al., 1996; Carbonell et al., 1996; Knapp et al., 1996). Here, the preservation of the crustal root and the lack of surface features associated with post-orogenic extension suggest that post-orogenic collapse did not occur (Berzin et al., 1996). Along the ESRU '93 profile (Fig. 4) in the middle Urals, Knapp et al. (1998) found that west of the Main Uralian fault zone the crustal thickness varies from ~48 to ~51 km. On the ESRU '95 profile (Fig. 4), abrupt thinning of the crust to ~45 km is suggested. Here, the east-dipping Main Uralian fault zone merges listrically with a zone of subhorizontal midcrustal reflectivity at ~15-km depth that truncates a series of large-scale antiforms and associated

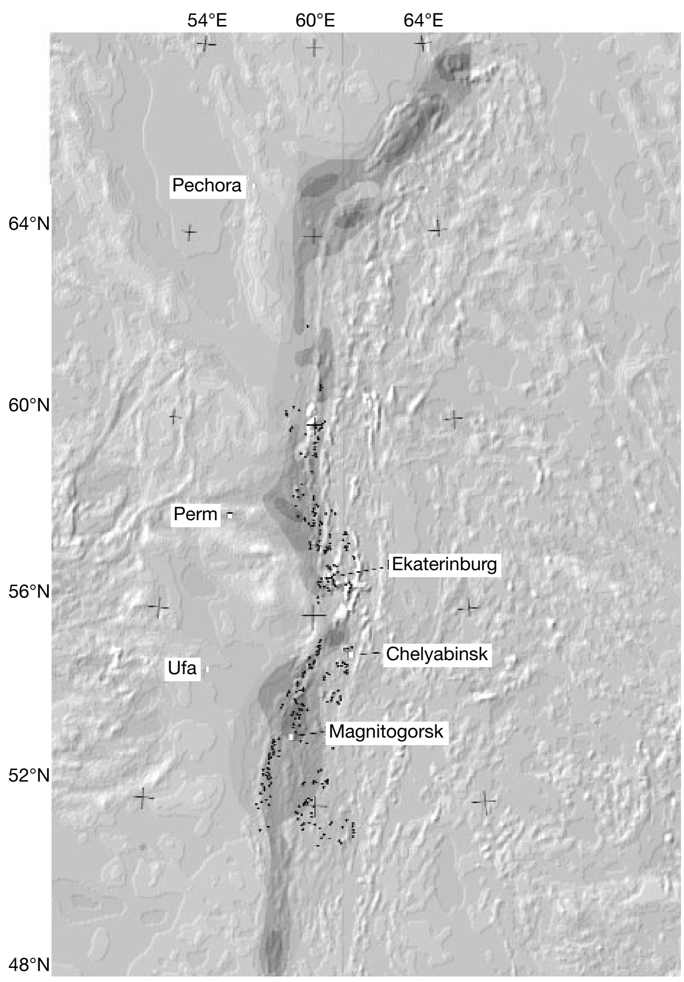


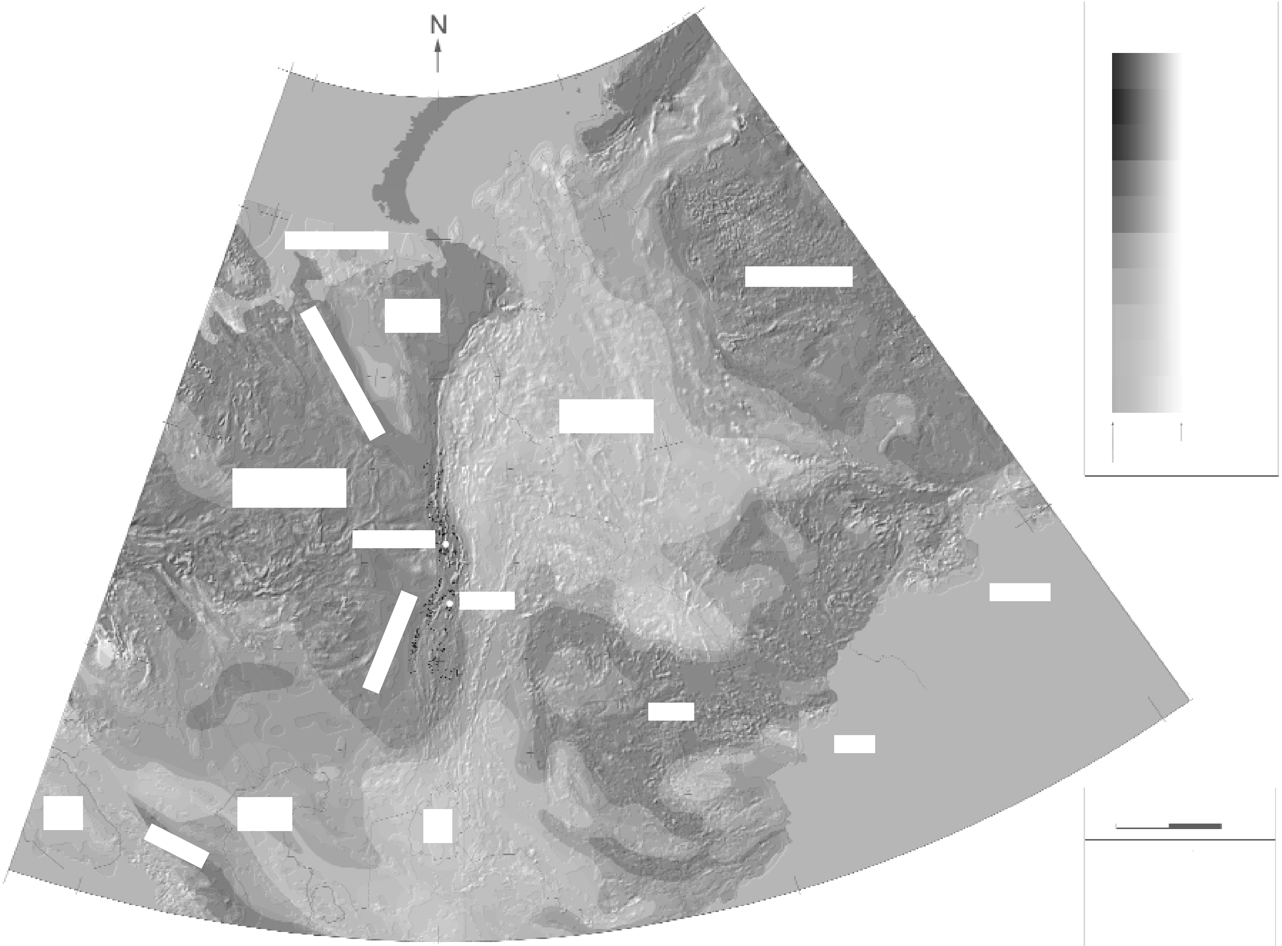
FIG. 10. The crustal thickness in the Urals (Bazhenov Geophysical Expedition; Gee and Zeyen, 1996) in dark gray tones, superimposed on the magnetic anomaly pattern in light gray tones in shaded relief (Fig. 9). The darkest level indicates depths of over 60 km. The thick crustal segments follow the magnetic grain of the Urals, with the exception of the northwest-striking crustal segment at about 58° N, east of Perm, which is taken up in the East European craton indenter. Gold deposits are shown as dots.

west-dipping shear zones of inferred Paleozoic age across the Uralian hinterland. Knapp et al. (1998) combined these observations with the overlying Triassic Imenovski graben as evidence of post-orogenic extension of the middle Urals in the early Mesozoic, in association with reactivation of the Main Uralian fault zone at the westernmost boundary of the West Siberian basin extensional province. This is in line with the westward extent of the high heat-flow density associated with the West Siberian basin (Fig. 11). The contrast in seismic reflection signatures with the southern Urals, which would appear to require a distinctly different tectonic history (Knapp et al., 1998), concurs with the variations along the length of the orogen emerging from the regional potential fields (Figs. 9-12).

In the map of crustal thickness (Fig. 10) the crustal root of the Urals is shown with elongate maxima between 60 and 65 km, which generally follow the trends of the magnetic anomalies and of the structures seen at the surface. However, at approximately lat 58° N, a prominent northwest-southeast–striking segment of the root deviates significantly from the overall north-south grain of the belt and the shallow structures in this part of the Urals. This segment is located west of the Main Uralian fault zone whereas the others are east of the Main Uralian fault zone. Although its nature and the significance of its deviating strike are at present unclear, we speculate a controlling role of Precambrian structures underlying the Timan Range (Fig. 4) and the northeastern margin of the East European craton. Here, Brown et al. (1999) show a northwest-southeast–striking Late Proterozoic-early Paleozoic (Cadomian) thrust belt.

The Bouguer gravity anomaly map (Fig. 12) reflects the Urals as a series of north-south–striking anomalies of between +10 and –10 mGal. The East European craton is characterized by values between –10 and –20 mGal. The Angara craton is reflected by a broad low with values between –50 and –150 mGal, which grades into even lower values in the Altaids of China and Mongolia. A broad northwest-southeast–striking anomaly, with values between –10 and –20 mGal, transverse to the Urals, is seen with its axis crossing the Urals at about 60° N to 60° E . This anomaly extends southeastward into the Altaids as far as 50° N to 80° E and northwestward along the Timan Range to the Barents Sea. The southern edge of this anomaly sets the southern Urals apart from the middle Urals. The northern edge of the anomaly is less sharply defined but corresponds with the transition between the middle and northern Urals as defined by the magnetic anomalies. The above major transverse Bouguer anomaly between the Barents Sea and the southeastern part of the West Siberian basin suggests a continuous heterogeneity in the deep crust and possibly the upper mantle, spanning about 30° long. Its nature is speculative, but it encompasses the above northwest-southeast–striking thick root segment and the middle Urals' bend in the magnetic anomaly pattern, and raises questions about remnants of the Timan zone extending east of the Urals.

In their analysis of the heat-flow density distribution in the Urals, Kukkonen et al. (1997) conclude that the present pattern and heat-flow density minimum of the Urals can be attributed to low crustal heat production in the subsurface of the Tagil and Magnitogorsk zones. Their models suggest that the measured surface minimum is not due to a decrease in mantle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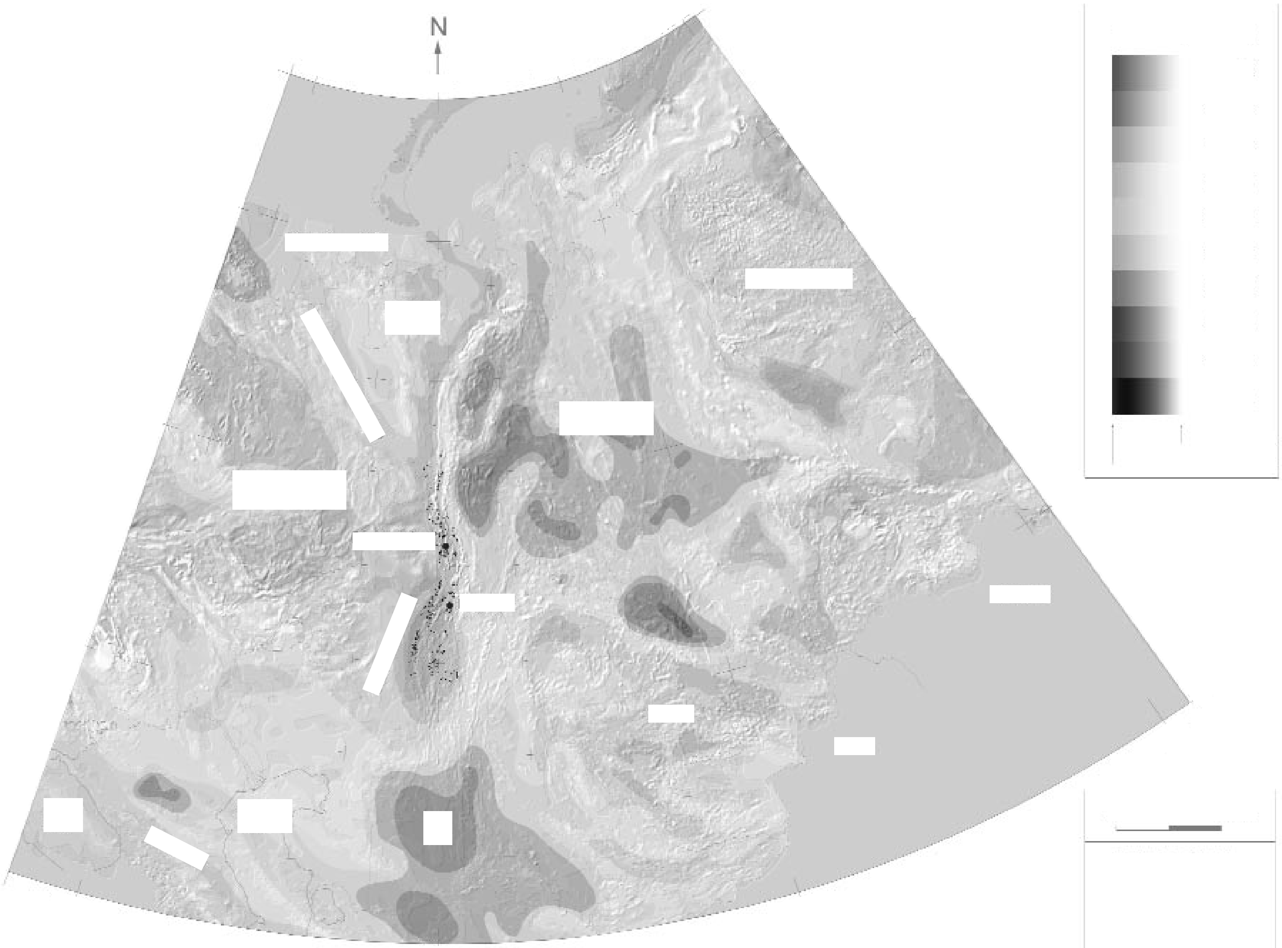
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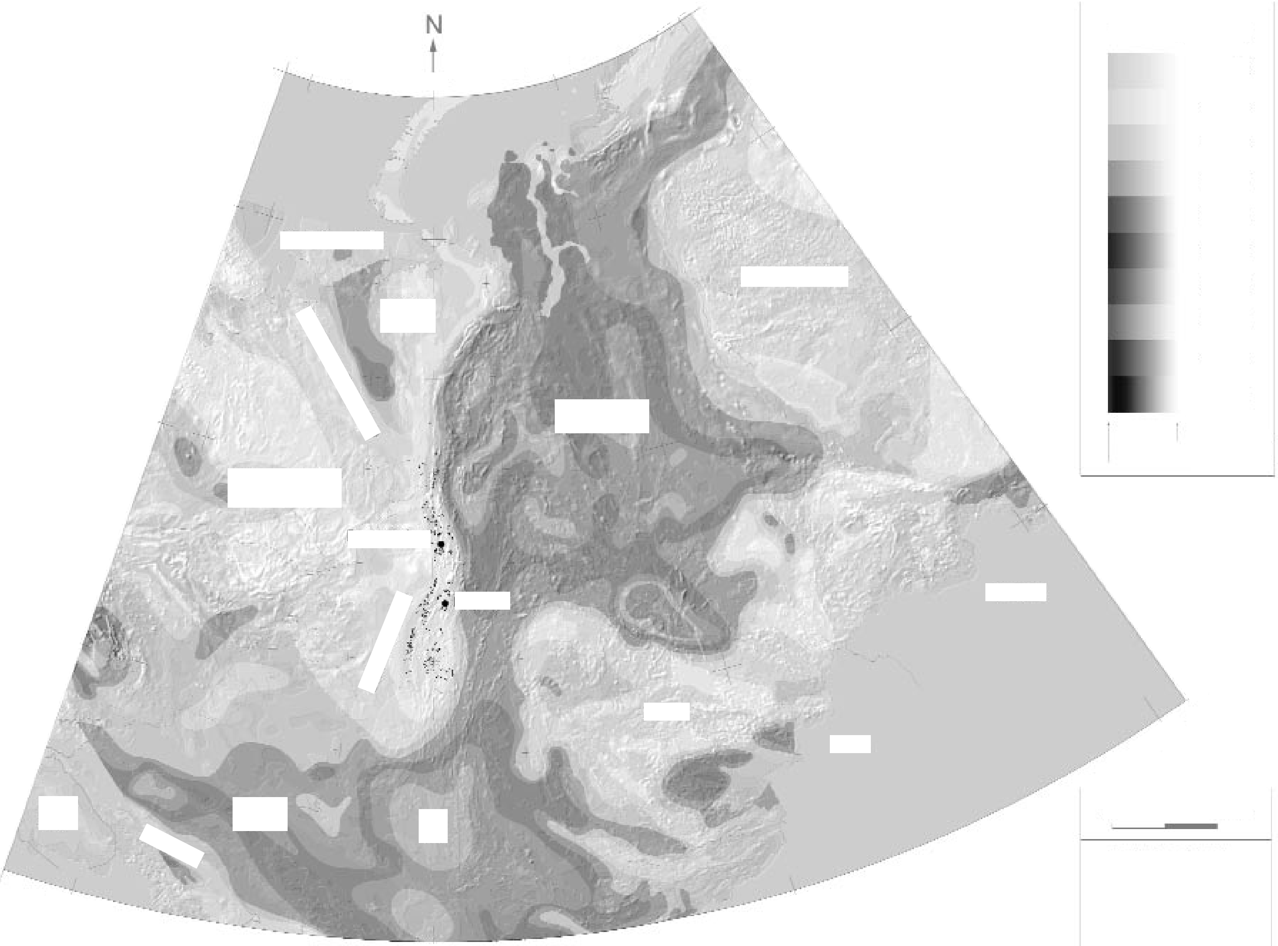
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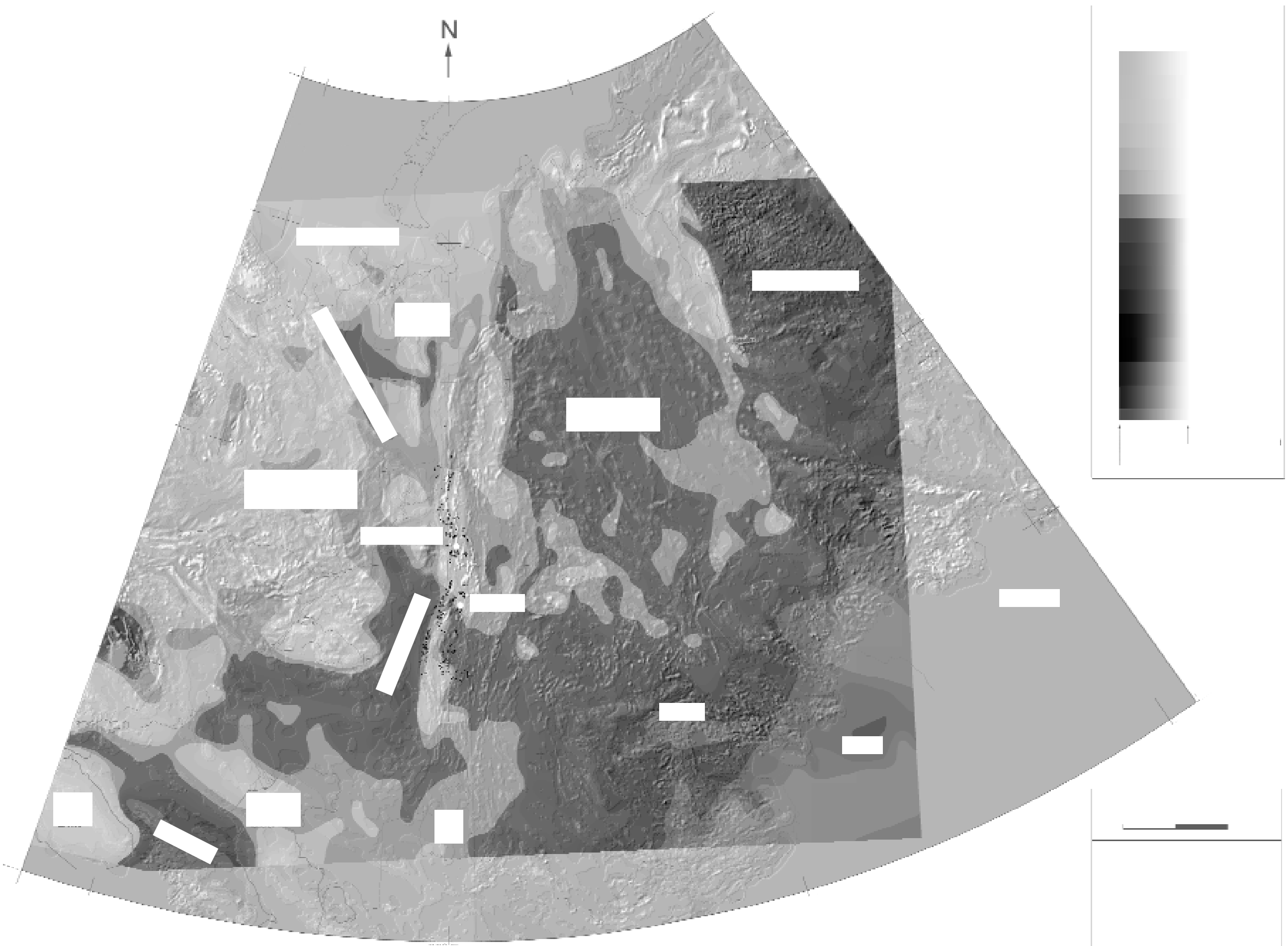
FIG. 11. The heat-flow density pattern of the region between the East European and Angara cratons (Ministry of Geology, USSR, 1977b) superimposed on the magnetic anomaly pattern in shaded relief (Fig. 9). The heat-flow density high corresponding to the West Siberian basin extends into the northern Urals as far west as the Main Uralian fault zone and as far south as the northern part of the middle Urals. Gold deposits are shown as dots.

heat-flow density or refraction effects in the lower crust. In the heat-flow density map (Fig. 11), the Urals are recognized as a north-south elongated low anomaly along the edge of a much larger low corresponding to the East European craton. South of lat 60° N, the Urals' low extends eastward to long 61° 30' E. Between lat 60° and 65° N it reaches only as far east as 60° E. The West Siberian basin is characterized by a broad heat-flow high between the lows of the East European craton and the Urals in the west, the Angara craton to the east, and the southern Altaids to the southeast. It connects to a high in the region of the Aral Sea. The highest heat flow values are reached in the northeastern Urals (50–60 mW/m^2) and the southern part of the West Siberian basin.

Integration of heat flow and magnetic maps in Figure 11 shows that the major western heat-flow low associated with the East European craton reaches far east across the southern and middle Urals. In the northern Urals, the major heat-flow high associated with the West Siberian basin reaches as far west as the Main Uralian fault zone. This produces a two-fold division between the southern and middle Urals on the one hand and the northern Urals on the other.

On the basis of Figures 9 through 12, we ultimately arrive at a three-fold division of the deeper structures of the Urals into southern, middle, and northern segments. This division relates to the configurations of an eastward indenter of the East European craton (e.g., Echtler and Hetzel, 1997; Echtler et al., 1997; Brown et al., 1999) into the middle Urals.

The middle Urals emerge as a structurally anomalous part of the orogen by contrasts in crustal thickness, deflection of the magnetic anomaly pattern, intersection with the prominent Timan Bouguer gravity anomaly, and the lateral transition in heat-flow density. These are emphasized by the northwest-southeast–striking Cadomian thrust belt in the Timan Range, an inferred lateral transition in the attitude and nature of the Main Uralian fault zone and lateral changes in late- to post-orogenic extension phenomena. In addition, the middle Urals segment is characterized by the greatest contraction, the only known high-temperature remobilization of the subducted and exhumed East European terrane, a significant sinistral translation component during convergence, and by granites crosscutting the Main Uralian fault zone (Echtler et al., 1997).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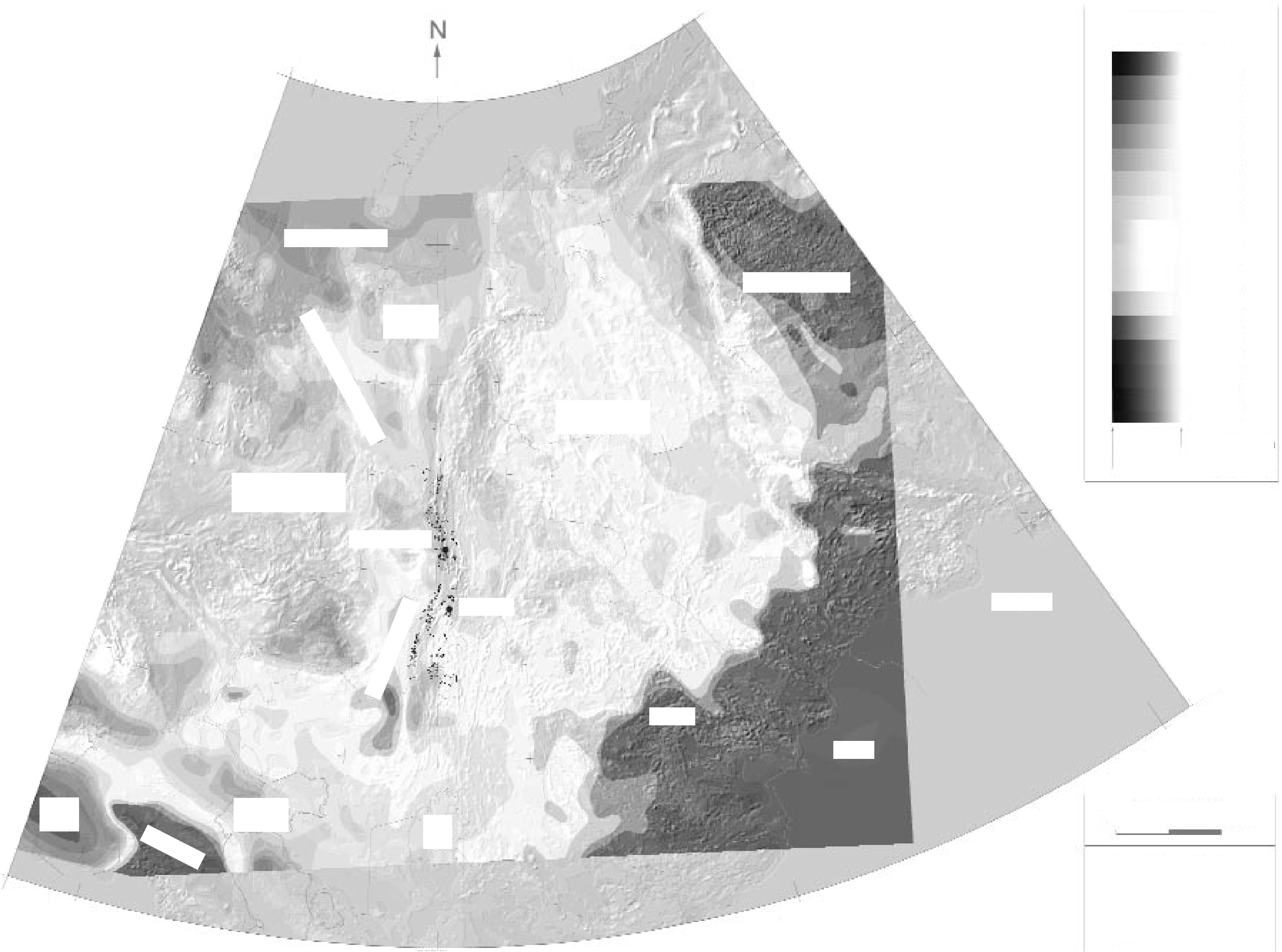
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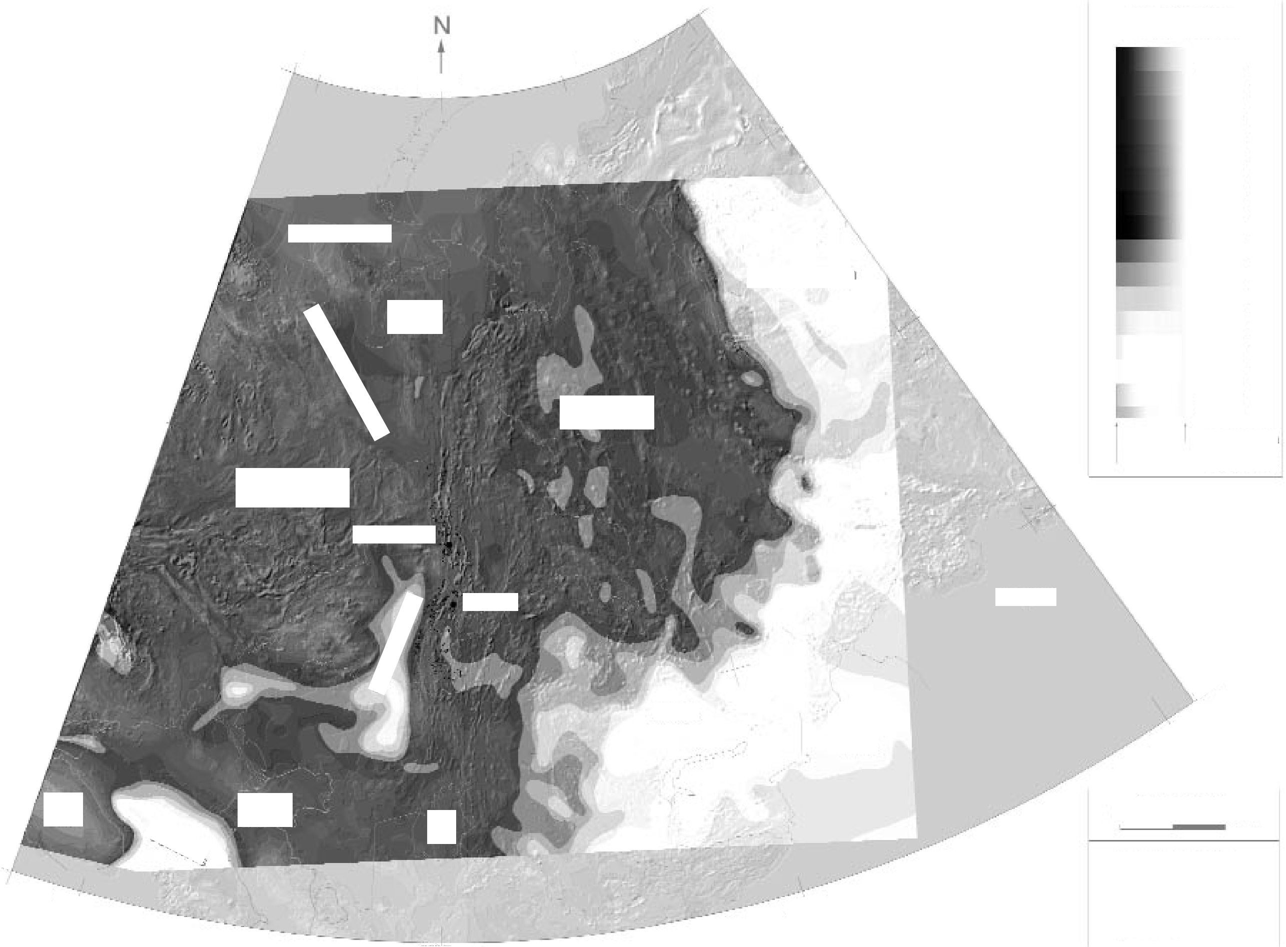
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FIG. 12. The Bouguer gravity anomaly pattern of the region between the East European and Angara cratons (Ministry of Geology, USSR, 1977a) superimposed on the magnetic anomaly pattern in shaded relief (Fig. 9). A broad Bouguer gravity anomaly high, from the Barents Sea to the southeast, transects the Urals. It separates the southern Urals from the middle Urals at about 55° N. Gold deposits are shown as dots.

On the basis of these configurations we postulate a singular transcrustal sidewall or oblique ramp in the subsurface of the middle Urals with potentially deep-reaching plumbing systems for heat and fluid flow (Fig. 13). Although within this segment there appears a prominent decrease in the number of known gold deposits, the largest known lode deposits at Kochkar and Berezovskoe are located, respectively, in its southern and northern margins, together with a cluster of deposits along the Main Uralian fault zone (Figs. 4, 9–12). The crudely symmetrical distribution of the gold deposits to the north and to the south suggests a first-order control by domains of extension related to indenter-associated escape tectonics. This concurs with late-orogenic dextral slip along the Main Uralian fault zone in the southern middle Urals (Echtler et al., 1997) and sinistral movement along the Serov-Mauk fault to the north (Bea et al., 1997). A primary control by this indenter is also suggested by the virtual absence of known gold deposits north of lat 60° N where the Urals border on the Pechora basin. This first-order distribution pattern may have been affected by indentation of the eastern Mugodzhar and Saldinsk massifs (cf. Yazeva and Bochkarev, 1996; Bankwitz et al., 1997).

Geodynamic Setting

Goldfarb et al. (1998) concluded that in the localization of gold deposits in the Pacific Rim, the role of the thermal regime was the most important factor other than tectonic style. De Boorder et al. (1998) suggested a relationship between late Cenozoic gold, mercury, and antimony deposits and increased heat flow, following detachment of subducted lithosphere and orogenic collapse during continent-continent collision within the European Alpine belt. Qiu and Groves (1999) attributed the prolific gold mineralization of the Yilgarn craton to a widespread thermal anomaly probably due to lithospheric delamination, following subduction-related accretion and continent-continent collision. Recently, Wyman et al. (1999) have suggested a link between lode gold deposits and Archean mantle plume–island-arc interaction in the southeastern Abitibi subprovince.

In this context, in the Urals, underplating of the orogen by mafic, mantle-derived magmas, as suggested by Bea et al. (1997), to produce the Permian-Early Triassic younger granites (Table 1) is significant. Their Ural-wide extent and magnitude of melt production, the suggested involvement of

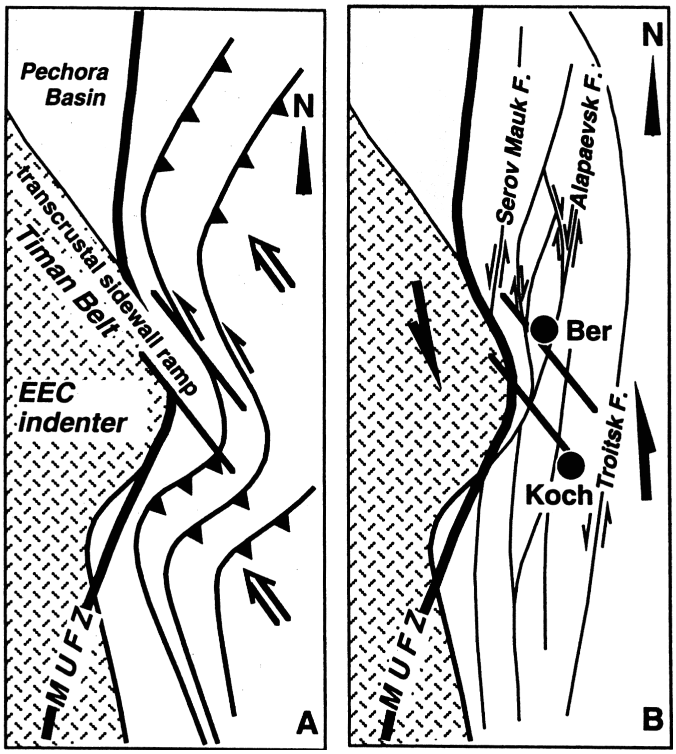

FIG. 13. Schematic outline of crustal shortening in the Urals. A. Convergence of the East European craton and the island arcs during the Devonian to Early Carboniferous, with initiation of a transcrustal sidewall ramp in the middle Urals. B. Further shortening during the Permo-Carboniferous in an overall sinistral transcurrent regime along steepened older thrusts. The Kochkar (Koch) and Berezovskoe (Ber) gold deposits are schematically shown as dots.

mantle processes, and a demonstrated mantle component in some of the younger granites (Bea et al., 1997; Gerdes et al., 1998) may imply some form of delamination in the lithosphere at this stage, possibly with the loss of a (the) subducted slab(s) and/or part of the thickened crust.

This appears contradictory to the prominently preserved orogenic root of the Urals and the limited extent of orogenic collapse. However, thickening of the crust and the lithosphere, in this case after an interval of synorogenic extension or noncompression, as inferred by Bea et al. (1997) and also by Echtler et al. (1997), remains a realistic option with the resumption of the compressive tectonic regime. The viability of crustal thickening in response to deep transpressive deformation is suggested by numerical experiments by Govers (1998) on the dynamics of ocean-continent and continent-continent transpressive regimes. This supports the suggestion by Puchkov (1997) of the mid-Carboniferous-Late Permian formation of the present Urals' root in the course of transpressional stacking or rigid collision (Table1). The alternation of phases of compression and extension suggested in Table 1 also raises a question of the potential significance of intermittent destabilization of the accretionary tectonic wedge for orogenic hydrothermal mineralization, in conjunction with changes in the stress regime, as suggested by White (1998) for the Yilgarn craton and by Lips et al. (1999) for the Carpathian-Balkan region.

Extensional collapse of the Magnitogorsk volcanic arc has been inferred in the Late Devonian to Early Carboniferous (Echtler and Hetzel, 1997; Brown et al., 1998), possibly following detachment of the subducted lithosphere (see also Chemenda et al., 1997). In the Magnitogorsk zone, this led to Early Carboniferous subsidence and the formation of carbonate deposits. In this interval, the older granitic rocks of Verkhisetsk and Shartashk were emplaced in a compressional regime, in the active continental margin of the Northwest island arc-continental sector. In the Early Carboniferous, the older granitic rocks of the Plast massif had formed, also during compression, in the continental zone of the Southeast island arc-continental sector. These were all followed by the emplacement of the Permian younger granites and by prominent gold mineralization during a period of extension.

In the Mindyak segment of the Main Uralian fault zone, structurally controlled fluid flow and gold mineralization coincided with a shift from orthogonally convergent to predominantly transcurrent deformation. The major transpressional continental shortening, inferred by Echtler and Hetzel (1997) to have taken place in the Permo-Triassic and by Puchkov (1997) in the mid-Carboniferous to Late Permian, was followed by transtension reflected by the formation of narrow Triassic rift basins at the time of widespread fluid-rock interaction and the local formation of small gold deposits. We see this latest extension event as related to the widespread Mesozoic extension in the Altaids, to the east, which were dominated by preceding sinistral transcurrent deformation (cf. Sengör et al., 1993; Allen et al., 1995; Sengör and Natal'in, 1996a, b; Rasulov et al., 1997).

Although these observations do suggest a relationship between magmatic processes, mineralizing fluid flow, and destabilization of the orogen, particularly the timing and the distribution of the intervening synorogenic extension need to be further detailed.

Conclusions

1. The Paleozoic Urals are part of a much larger orogenic belt between the East European craton in the west and the Angara craton in the east. The Urals resulted from the collision of the East European craton with two island arcs in the west, in the Magnitogorsk and the Tagil zones, fragments of continental crust, and poorly known island arcs to the east of these zones. Deep seismic studies show a bivergent structure in the southern part of the Urals.

2. In the Devonian, collision commenced in the south and dominantly sinistral transpression and sedimentary facies shifted diachronously to the north. Along the western margin of the Urals, closure of oceanic basins involved westward obduction of oceanic lithosphere over the East European craton and eastward subduction, possibly also of part of the margin of this craton, followed by exhumation of high-pressure rocks. The principal suture is along the Main Uralian fault zone. Along the eastern margin of the Urals there are indications of westward subduction of oceanic lithosphere and volcano-sedimentary arcs.

3. A series of early to middle Carboniferous older granites was emplaced during compression. Locally, these have been demonstrated to result from melting of subducted oceanic lithosphere.

4. Synorogenic extension is reflected by the Early Carboniferous extensional collapse of the Magnitogorsk island arc, in the south, and by the Permian to Early Triassic emplacement of widespread younger granites. These granites have been suggested by Bea et al. (1997) to result from a thermal event following underplating of the crust by mantle-derived mafic magmas.

5. The late- to post-orogenic history of the Urals is characterized by the formation of Triassic rift basins within and along the eastern margins of the belt. Extensional orogenic collapse has been inferred in the middle Urals in relationship to the formation of the West Siberian basin.

6. The tectono-magmatic model developed by Fershtater et al. (1997) for the Urals constitutes a useful framework for the discussion of the evolution of the gold deposits. This model distinguishes a Suture sector in the west, along the Main Uralian fault zone, from the north-south–striking, tectonically imbricated Northwest and Southeast island arc-continental sectors to the east, each formed of an island-arc zone, a transitional zone, and a continental zone. Gold deposits occur throughout all the tectono-magmatic zones. The ages of a number of the gold deposits have been estimated from a limited number of K-Ar analyses of associated alteration assemblages.

7. In the Magnitogorsk island-arc zone, gold deposits such as Safyanovka and Murtikti, are closely associated with volcanic-hosted massive sulfide-type and disseminated base metal mineralization and gold is mostly enclosed in pyrite. However, younger structures have controlled the deposition of higher gold grades, which are located in shear zones, faults, and their intersections. Magnetite and copper-magnetite skarns and porphyry copper systems occur in active continental or transitional zones, which are often tectonically imbricated with island-arc complexes.

8. The most prominent gold deposit within the Auerbakh-Krasnoturinsk group of Devonian auriferous copper-magnetite skarns and porphyries is the younger, Late Carboniferous Vorontsovsk gold deposit, which is clearly structurally controlled. These and other examples suggest that regional deformation and concomitant hydrothermal fluid-rock interaction incorporating all tectono-magmatic zones in the Late Carboniferous-Early Triassic upgraded the gold grades of earlier deposits.

9. The principal known gold deposits are those of Berezovskoe, in the active continental margin of the Northwest island arc-continental sector, and Kochkar, in the continental zone of the Southeast island arc-continental sector. Here, gold quartz lodes occur within and along the margins of Carboniferous batholiths of older granite. The inferred ages of the lodes suggest that these are largely coeval with the mainly undeformed Permian-Early Triassic younger granites; however, a spatial association with the younger granites has not been observed. Many small gold deposits are hosted by shear zones where granites are inconspicuous. The conclusions reached by Kisters et al. (1999, 2000) concerning the dominant structural-chemical control of the lodes at Kochkar and at Mindyak (along the Main Uralian fault zone) can be extended throughout the Urals.

10. The integration of magnetic, heat-flow, gravity, and crustal thickness data leads to the recognition of the significance of the East European craton indenter along the western edge of the middle Urals segment. A corresponding major, north-northwest-south-southeast–striking, transcrustal sidewall or oblique ramp is inferred in the subsurface of this segment, with potentially deep-reaching plumbing systems for heat and fluid flow. The world-class Kochkar and Berezovskoe deposits occur along the southern and northern boundary zones of this ramp and could be a measure of this system. The symmetrical distribution of additional gold deposits to the north and to the south suggests a relationship to indenter-associated escape tectonics.

11. The widespread distribution of late-orogenic gold-bearing quartz lodes, their close temporal relationship with the younger granites, together with the Permian upgrading of older gold deposits indicate a common metallogenic factor in the evolution of the Urals. This could reside in the thermal flux related to mantle-derived mafic magmas underplating the crust, as suggested by Bea et al. (1997), to explain the Ural-wide melting event leading to the formation of the younger granites. Because of the very large extent of this event during a phase of synorogenic extension and a change from convergent to transcurrent deformation, and because of the involvement of mantle processes, we suggest a relationship with regional-scale delamination in the lithosphere in association with changes in stress regime. A Ural-wide, late phase of hydrothermal fluid flow with local gold mineralization during the formation of transtensional rift basins in the Triassic emphasizes the significance of changes in stress regime for the formation of hydrothermal mineralization.

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