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AN OVERVIEW OF THE TECTONIC SETTING AND STYLES OF MINERALIZATION AND ALTERATION OF LODE-GOLD DEPOSITS IN THE LATE-PALEOZOIC SOUTHERN URALS, RUSSIA

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by

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ABSTRACT

The late-Paleozoic Uralides represent one of the largest lode-gold metallogenic provinces in the world. In the southern Urals, gold distribution is heterogeneous and is mainly confined to two tectonostratigraphic zones, namely the Main Uralian Fault and the East Uralian Zone. The important lode-gold districts within and in the immediate hanging wall of the first-order crustal suture of the Main Uralian Fault are characterized by a complex tectonic history of earlier compressional tectonics involving thrusting, folding and reverse faulting and later transcurrent shearing. Gold mineralization is hosted by second- and third-order brittle to brittle-ductile strike-slip faults that developed late during the kinematic history of the Main Uralian Fault. Strike-slip reactivation of earlier compressional structures was related to the late-stage docking of the passive margin of the east European Platform with island-arc complexes of the southern Urals, an event that is tentatively related to changes in plate motion during the final stages of terrane accretion during the upper Permian and lower Triassic. Gold mineralization was controlled by the permeability characteristics of the hydrothermal conduits, as well as by competence contrasts and geochemistry of the mainly volcanic host rocks. Mineralization occurred at relatively shallow crustal levels (2-6 km) and largely post dates peak-metamorphism of the host rocks. The large and very large (up to 300t Au) gold deposits of the East Uralian Zone are hosted by upper-Paleozoic granitoid massifs. Gold mineralization is temporally associated with the main phase of regional-scale compressional tectonics and granite plutonism during the upper Carboniferous and lower Permian. Controlling structures have a dominantly east-west strike and occur as hybrid shear-tensional vein systems in competent granitoids subjected to E-W directed regional shortening. Deformation textures and alteration mineral assemblages indicate lower-amphibolite facies conditions of mineralization close to peak metamorphic conditions that are associated with the mid-Permian regional metamorphism and tectonism.

Gold deposits in the southern Urals are, therefore, polygenetic and are temporally and genetically distinct in each of the two major mineralized tectonostratigraphic zones of this well-preserved collisional orogenic belt. The different timing of ore fluid generation and fluid discharge is interpreted to be the result of the different tectonic, metamorphic, and magmatic evolution of terranes in the southern Urals.

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INTRODUCTION

Over the past decade, lode-gold deposits have been recognized as the vestiges of large-scale fluid-flow systems whose formation is temporally and spatially related to tectonic, metamorphic and magmatic processes in convergent margin orogens (Colvine, 1989; Kerrich and Cassidy, 1994; Miller et al., 1994; Groves et al., 1995). This relationship between orogenic processes and ore formation is emphasized by the occurrence of large gold metallogenic provinces during three main periods in Earth history, namely the late-Archaean, the late-Mesozoic-Cenozoic and, to a lesser extent, the mid-to-late Paleozoic. During each of these times, fragments of continental and oceanic crust were assembled and subsequently fragmented to define global supercontinental cycles of crustal evolution (e.g Woodall, 1988; Groves and Foster, 1990; Nesbitt, 1990; Kerrich and Cassidy, 1994). Amongst Paleozoic mountain belts, the Uralides in central Russia (Fig. 1) represent one of the most productive lode-gold metallogenic provinces in the world, matched, in terms of gold output, only by the mid-Paleozoic Lachlan fold belt in southeastern Australia (Smirnov, 1976; Sandiford and Keays, 1986). Recent geophysical and geological work has emphasized a number of outstanding geological features that make the Urals a unique study area for the evolution of lode-gold deposits in collisional orogens. These include, amongst others, the lack of a post-collisional collapse that might have overprinted primary orogenic features, the preservation of an anomalously thick crustal root, the occurrence of exceptionally well-preserved island-arc and ophiolite successions and elongate domes of high-P/low-T metamorphic massifs. In particular, the wide range of syn- and epigenetic mineral deposits recorded in the Uralides (Berzin et al., 1996; Echtler et al., 1996; Brown et al., 1997; Puchkov, 1997; Koroteev et al., 1997) make it a fruitful area of study for ore genesis. However, the geological setting, styles of mineralization and alteration, size and even location of mineral occurrences in the Urals are virtually unknown in the international literature, so that the significance of the Uralides as one of the best preserved and economically most important Paleozoic orogenic belts is largely overlooked.

The aim of this paper is to present an overview of the geological setting, styles of mineralization and associated alteration of lode-gold deposits in the central South Urals, namely the region between the towns of Chelyabinsk in the north and Magnitogorsk in the south (Fig.2). The present-day understanding of the collisional tectonics of the Urals will be briefly reviewed, with particular focus placed on the internal parts of the orogen where the majority of gold deposits are located. Radiometric ages and stable isotope data that could constrain the timing and origin of mineralization and alteration are scarce, but structural and geological relationships facilitate a relative geochronological framework that can be used to relate gold mineralization to distinct episodes in the tectonic evolution of the southern Urals.

REGIONAL GEOLOGY

The Uralides form a bivergent fold-and-thrust belt wedged between rocks and cover sequences of the East European Platform in the west, intervening island-arc and ophiolite successions and a complex agglomerate of microplates and terranes of the Siberian and

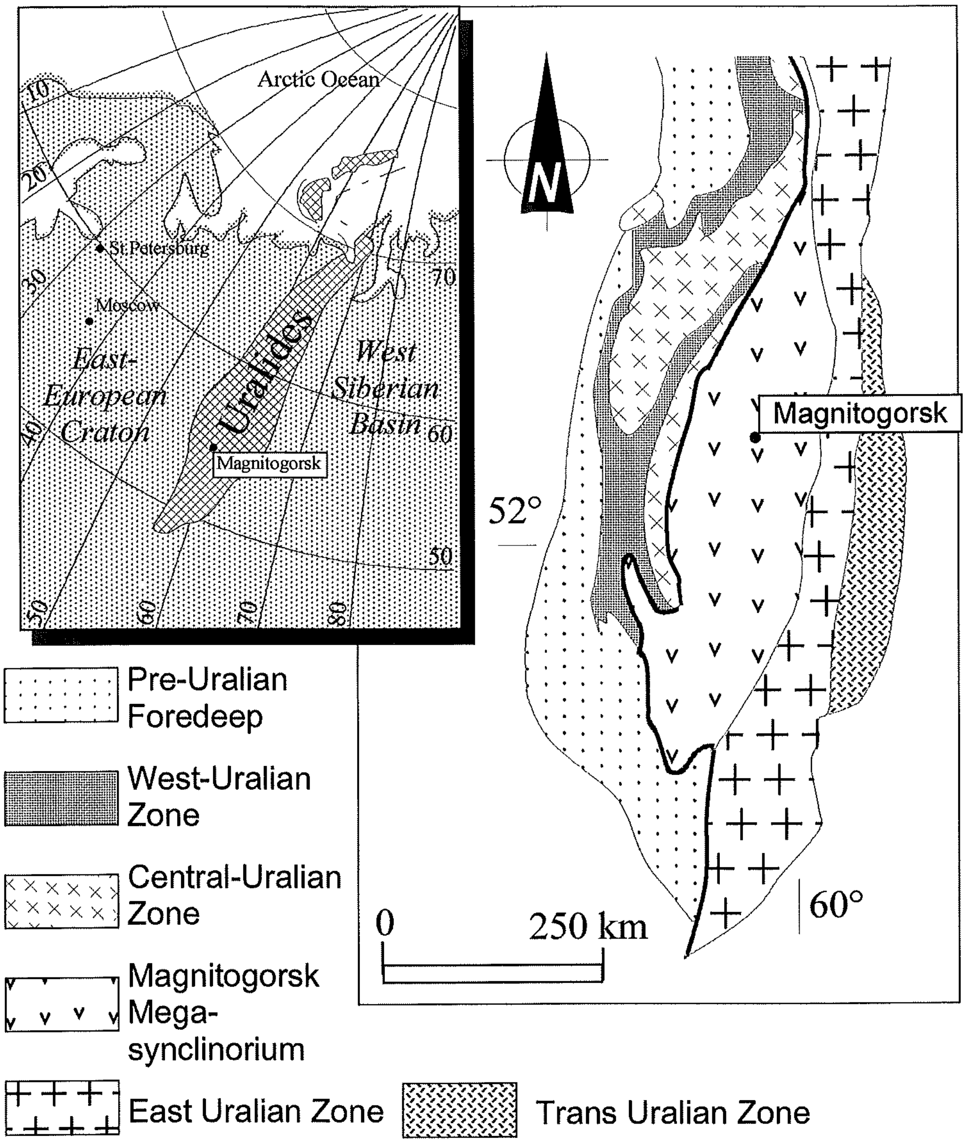


Fig. 1: Location of the Uralides between Europe and Asia and the distribution of tectonostratigraphic zones in the southern Urals (after Puchkov, 1997).

Kazakhstan Cratons in the east.This distinctly linear, N-S trending orogen can be traced along strike for over 2500 km and forms the geological and topographic divide between Europe and Asia. The Urals have been affected, in the main, by convergence and collision of the bounding cratons during the upper-Paleozoic (Zonenshain et al., 1984, 1990; Puchkov, 1997). Based on tectonostratigraphic lithologic associations, the Urals have traditionally been divided into three external zones in the west and three internal zones in the east (Fig. 1) (e.g. Ivanov et al., 1975; Zonenshain et al., 1984, 1990; Seravkin et al., 1992; Matte et al., 1993; Berzin et al., 1996; Brown et al., 1996; Echtler et al., 1996; Puchkov, 1997). The external zones include a foreland basin, a west-vergent fold-and-thrust belt developed on the passive continental margin of the East European Platform, and a zone of high-grade metamorphic complexes. The internides are made up of mid-Paleozoic, largely autochthonous to parautochthonous island-arc, back-arc and oceanic sequences of the Magnitogorsk Megasynclinorium, followed in the east by a succession of intensely deformed and polyphase metamorphosed lower- to mid-Paleozoic ophiolites and island-arc complexes of the East Uralian Zone that have been intruded by complex, upper-Paleozoic granite-gneiss massifs. The easternmost zone comprises a heterogeneous assemblage of variably metamorphosed volcanics, sediments and granitoids that belong to the Trans Uralian Zone. The boundary between the externides and the internides is represented by a crustal-scale suture zone, the Main Uralian Fault (Figs. 1 and 2), which forms an east-dipping mélange zone that can be traced for over 2000 km throughout the Urals. In the east, the orogenic wedge is bounded by a series of west-dipping faults that are poorly exposed due to younger cover sediments overlying most of the Trans Uralian Zone.

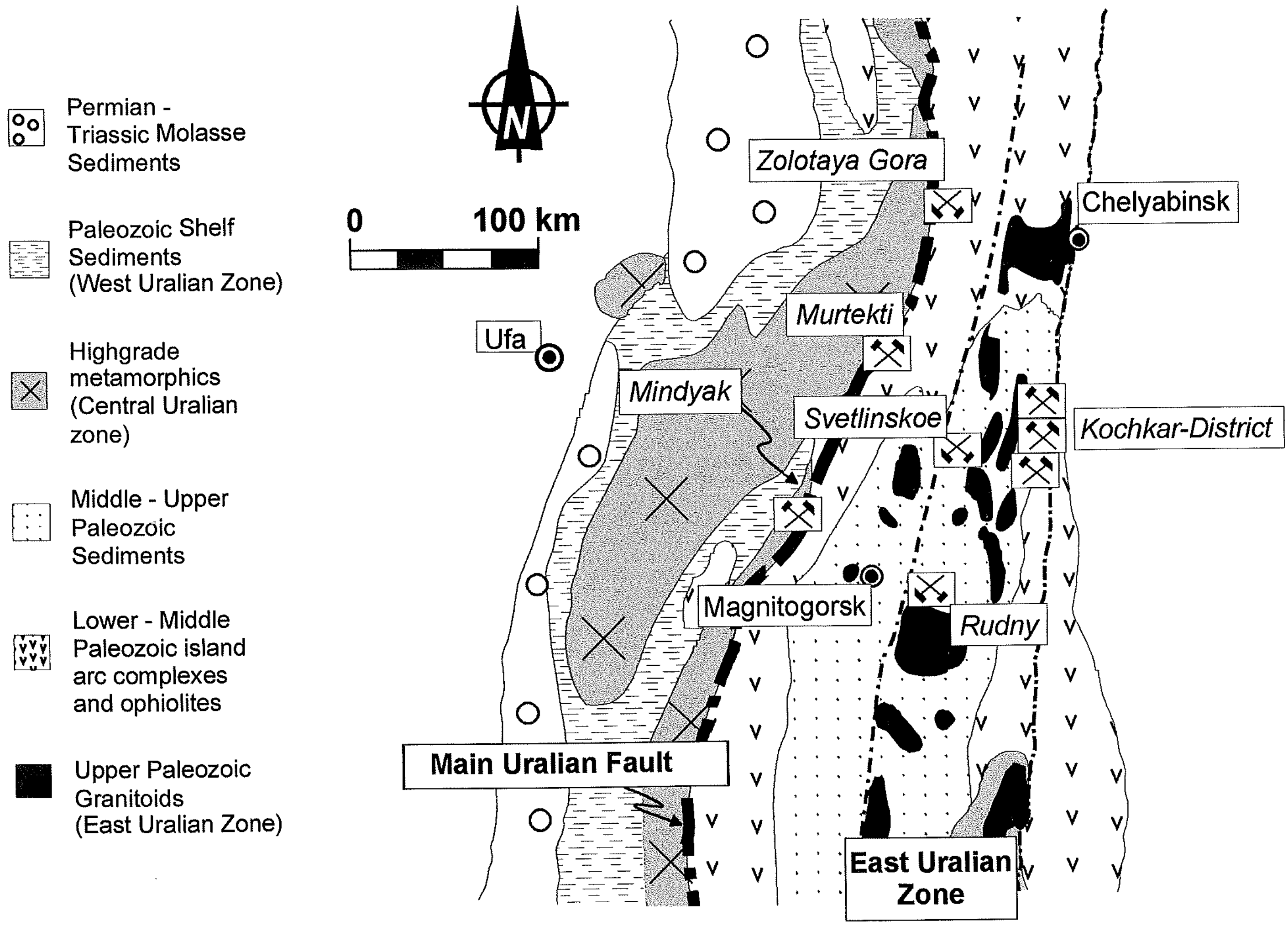


Fig. 2: Simplified geological map of the south central Urals also showing the location and distribution of the main lode-gold districts (modified after Berzin et al., 1996).

It is now widely accepted that the geological evolution of the Urals records a complete Wilson-type cycle as it was initially suggested by Hamilton (1970). This evolution commenced in the late-Cambrian with continental rifting along the eastern edge of the East European Platform. Continued seafloor spreading led to the formation of a passive continental margin facing an Uralian ocean in the east that contained island arcs and associated back-arc basins which were mainly active during Silurian and Devonian times. Spreading was reversed during the mid-Devonian subduction of oceanic crust below island-arc complexes that are preserved within the Magnitogorsk Megasynclinorium. Recent studies have suggested that subduction was mainly directed to the southeast, i.e. oblique to the N-S trending plate boundary (Puchkov, 1997; Echtler et al., 1997). Structural evidence such as the W-verging imbrication of, for example, the Kraka allochthone onto the western foreland and N-S trending fold structures and thrusts in the middle Urals do not, however, support a distinctly oblique convergence, but rather frontal, E-W directed subduction and collision (e.g. Seravkin, 1997). A period of widespread I-type granitoid plutonism in the East Uralian Zone of the middle and southern Urals was largely coeval with subduction (Fershtater et al., 1997, Bea et al., 1997). Following a period of tectonic quiescence during much of the Carboniferous, a final collisional stage in the Urals occurred during upper Carboniferous and Permian times and lasted until the lower-Triassic (Zonenshain et al., 1984; Puchkov, 1997). Deformation is manifest by mainly thin-skinned thrust tectonics in the externides (Brown et al., 1996; Perez-Estaun et al., 1997) and a major phase of compressional and later transcurrent tectonics along the Main Uralian Fault. In the internides, deformation was strongly partitioned along N-S trending shear belts and involved regionally variably developed thrusting, strike-slip shearing, regional metamorphism and a second phase of voluminous granitic plutonism in the East Uralian Zone.

LODE GOLD DEPOSITS IN THE SOUTHERN URALS

Gold deposits and prospects are common throughout the southern Urals, but in terms of gold production and the distribution of medium- to large deposits, two distinct tectonostratigraphic zones appear to be particularly fertile. These include the Main Uralian Fault and the East Uralian Zone (Figs. 1 and 2). The former hosts a number of small- to medium-sized deposits (1-10 and locally > 30 t Au) that occur mainly in volcanic rocks within and in the immediate hanging wall of the fault zone. The latter contains a number of medium- to very large deposits (up to ≥ 300 t Au) that are predominantly hosted by upper-Paleozoic granitoid massifs forming the 'plutonic axis' of the southern Urals. In the following section a brief account is given of the main geologic features of the two zones and the characteristics of lode-gold deposits found within them.

MAIN URALIAN FAULT (MUF)

The MUF has traditionally been regarded as the main orogenic suture between the external and internal zones of the Urals (Hamilton, 1970; Ivanov et al., 1975; Zonenshain et al., 1984). On surface, the fault zone is expressed as a 3 to 20 km wide mélange zone that comprises a heterogeneous assemblage of imbricated mid- to upper-Paleozoic mafic-to-felsic volcanics, volcanoclastics, clastic and chemical sediments, together with voluminous ultramafic massifs. In seismic profiles, the MUF occurs as a wide, shallow-to-moderate, easterly dipping reflector that can be traced to depths of at least 15 km (Juhlin et al., 1995; Berzin et al., 1996). Rocks of the mélange show sub-to-lower-greenschist facies grades of metamorphism. They are characterized by low strain, except where they are in proximity to larger faults, such that the original textures and structures are preserved.

The kinematic evolution of the MUF is only poorly understood. Correlation of deformation events along the MUF is complicated by the diachronous nature of deformation that progressed with time from south to north (e.g. Zonenshain et al., 1990; Eide et al., 1997; Puchkov, 1997), the scarcity of radiometric age data that can be used to constrain deformation events, and by the irregular geometry of the colliding plate boundaries. Despite these difficulties, most studies agree that the kinematic history of the MUF was long lived and accommodated a major period of convergence and compressional tectonics, followed by crustal adjustments long after initial terrane docking and accretion that involved mainly transcurrent shearing (Zonenshain et al., 1990; Puchkov, 1997; Table 1).

Early compressional tectonics, henceforth denoted D1, are evidenced by W- to NW-directed thrusting and imbrication of thrust allochthones that are preserved as large ophiolitic klippen structures on rocks of the western foreland (e.g. the Kraka klippe). This 'soft collisional stage' (after Puchkov, 1997) is thought to represent the mid-Devonian to lower-Carboniferous subduction and convergence of the bounding cratons before the actual collision. Recent models have suggested an oblique, SE-directed convergence and subduction during the soft collisional stage (e.g. Echtler et al., 1997), but the kinematics along early thrust faults suggest an essentially W-verging transport of thrust sheets, which rather indicates an E-W directed convergence subnormal to the plate boundaries. Thrusting of upper-Viséan sediments constrains the onset of major compressional tectonics along the MUF to the upper-Carboniferous. This stage is the dominant deformation recorded in rocks of the MUF and is referred to as the 'rigid collision' (Puchkov, 1997). Compressional tectonics include an initial phase of NW-directed thrust imbrication of allochthonous volcanosedimentary units (D2), NW- and, locally, SE-verging folding of the thrust pile (D3), and subsequent reverse faulting along NE-SW trending faults that are roughly axial planar to D3 folds, including both SE- and NW-dipping faults (D4) (Table 1). As a result of the D3 folding and D4 faulting, lithologies show predominantly steep-to-moderate southeasterly dips. The mainly compressional tectonics are succeeded by a stage of transcurrent deformation being characterized by both sinistral and dextral strike-slip faults during which many of the older thrusts and reverse faults were reactivated. Sinistral strike-slip faulting (D5) along steeply inclined, northerly trending faults is widespread in the middle and southern Urals and is followed by dextral strike-slip kinematics (D6), which is most prominently developed along the MUF in the southern Urals. Regional-scale extensional tectonics are conspicuous by their absence, although minor graben structures filled with Permian and lower Triassic molasse-type sediments occur in the internides (Puchkov, 1997). Fission-track analyses by Seward et al. (1997) indicated a cessation of tectonics along the MUF since the lower Triassic. Uplift and erosion rates were low and likely to be less than 5 km since then.

In addition, recent investigations by, among others, Chemenda et al. (1997), Echtler et al. (1997) and Echtler and Hetzel (1997) argued that the basal parts of the MUF have acted as a normal detachment that accommodated the uplift and exhumation of high-pressure, low-temperature metamorphic complexes in the footwall of the fault. The timing of the exhumation has yet to be constrained by radiometric age data, but is likely to have occurred during the upper-Devonian, shortly after the subduction of the Uralian ocean (Hetzel et al., 1998).

Table 1: Compilation of tectonic phases along the Main Uralian Fault as recorded within, and in the surroundings of, the Mindyak deposits and its western foreland

Deformation phase	Type of deformation	Inferred timing of deformation
D1	W-directed thrusting of nappes onto the western foreland (e.g. Kraka Klippe)	late-Devonian to lower-Carboniferous
D2	W- to NW-verging thrust imbrication within the Main Uralian Fault (s.s.)	upper-Carboniferous to Permian
D3	Upright to (W-) NW-verging folding of thrust pile	
D4	SE- (NW-) dipping reverse faults	
D5	oblique, sinistral strike-slip faulting mainly along reactivated D4 faults	
D6	steeply dipping, NE-SW trending dextral strike-slip faults and subsidiary structures	Upper-Permian to lower-Triassic (?)
D7	small-scale normal faulting	

EAST URALIAN ZONE (EUZ)

One of the most striking features of the internides east of the MUF is the network of N-S trending shear belts that divide the central South Urals into broadly linear, up to 1000 km long and several tens of kilometres wide domains, each of which is characterized by different lithostratigraphic associations, internal strain and metamorphic grades. The EUZ, that hosts the largest gold deposits in the Urals, forms the central zone of the internal parts of the southern Urals (Figs. 1 and 2). In the west it is juxtaposed against mainly unmetamorphosed island-arc successions and overlying sediments of the Magnitogorsk zone along the Kumljak-Swetlinsk-Strelezk shear zone system. In the east it borders along the Dzahbyk-Karagai-Plast shear zone against rocks of the Trans Uralian Zone. Deformation in the bounding shear belts involved oblique, mainly NW-SE to E-W directed compression resulting in predominantly sinistral strike-slip to oblique-slip kinematics (Bankwitz et al., 1997). Deformation proceeded probably intermittently from the Carboniferous to the late-Permian and, possibly, lowermost Triassic.

Rocks of the EUZ are characterized by greenschist-to-widespread amphibolite-facies metamorphic grades that contrast markedly with the mainly unmetamorphosed successions of the Tagil-Magnitogorsk Megasynclinorium in the west so that the EUZ is also referred to as the East Uralian uplift in the Russian literature (e.g. Zonenshain et al., 1984). Lithologically, the EUZ comprises a succession of lower-to-mid-Paleozoic volcanics, volcanoclastics and sediments interpreted to represent remnants of island-arc and ophiolite complexes. A specific feature of the EUZ is the occurrence of large granitoid massifs, that form the 'plutonic axis' of the south Urals. Based on petrography and radiometric age constraints, two main types of granitoids can be distinguished (Fershtater et al., 1997; Bea et al., 1997): an earlier upper-Devonian to lower-Carboniferous (360-320 Ma) tonalite-trondhjemite-granodiorite (TTG) suite, and a later upper-Carboniferous to lower-Permian (290-265 Ma) suite of 2-mica, microcline-bearing granites. In the central South Urals, these granitoids typically form elongate, N-S trending massifs parallel to the trend of the EUZ. Texturally, numerous granite massifs display a zonation from outer, strongly foliated gneisses to more porphyritic textures in the central parts of individual plutons. Gradual transitions in fabric development are often marked by wide zones of schollen- and raft migmatites and numerous generations of aplite- and pegmatite-dykes indicating repeated episodes of granite emplacement. Petrographically, a similar zonation is observed from outer tonalites and trondhjemites to progressively granodioritic and granitic compositions in the core of plutons. Based on detailed fabric studies, radiometric age constraints and the characteristic elongate shape of plutons, Bankwitz et al. (1997) and Kröner et al. (1998) suggested a synkinematic emplacement of granite plutons into oceanic and island-arc rocks during sinistral transcurrent and/or transpressive shearing along the shear belts.

GOLD DEPOSITS ALONG THE MAIN URALIAN FAULT

Introduction

The major features of lode-gold deposits along the MUF in the central south Urals are described below. This review is based on available studies from Russian literature (e.g. Smirnov, 1976; Sazonov et al., 1989; Dimkin et al., 1990; Seravkin et al., 1992, 1994; Koroteev, 1996; Koroteev et al., 1997) and our own work, and is intended to outline characteristics of lode-gold deposits that may be used to compare gold deposits of the MUF with the geological setting and timing of other deposits in the central south Urals.

Nature and size of deposits

The majority of lode-gold deposits located along and within the immediate hanging wall of the MUF are rather small with past production and estimated reserves of less than 1-2 t Au. However, there are two main ore fields, namely the Mindyak and Murtekti districts (Fig. 2), that have produced >30-50 t Au. In recent years, the two districts have been mining grades in the range of 4-8 g/t in underground operations, but considerably higher grades were documented in historic times. In the Russian literature, gold deposits along the MUF are grouped, according to the style of mineralization, into quartz (± carbonate) vein deposits, disseminated and stockwork-type mineralization, and rodingite-type deposits. Transitions between gold-quartz lodes and disseminated styles of mineralization are common on a deposit scale (e.g. at Murtekti). Rodingite-type deposits, such as those at the Zolotaya Gora deposit (Fig. 2), represent vein- or dyke-like skarnoid diopside-garnet-chlorite-apatite-magnetite-rich rocks hosted by ultramafic massifs that typically line the trace of the MUF in the southern and middle Urals (Savelieva et al., 1997). However, the timing and origin of auriferous rodingite dykes with respect to the formation of the ultramafic massifs is still unclear.

Structure

Structure is the single most important factor controlling the distribution of gold deposits along the MUF, and the geometry and orientation of ore shoots in the deposits. On a regional scale, gold deposits are aligned parallel to the trend of the MUF, being confined to a relatively narrow, but elongate corridor that delineates the trace of the first-order crustal fault. Gold mineralization is hosted adjacent to and between second-order brittle and subordinately brittle-ductile fault zones of mainly northerly to northeasterly strike. Second-order structures are steeply inclined and of limited strike extent (< 2-4 km). Most of the faults are characterized by dextral strike- or oblique-slip kinematics. Overprinting and cross-cutting relationships indicate that faults have developed late in the kinematic evolution of the MUF during reactivation of early compressional structures such as thrusts (D2) and reverse (D4) faults (Fig. 3). The faults typically form an anastomosing pattern enclosing lozenge-shaped domains characterized by the development of complex sets of third-order faults and fracture zones

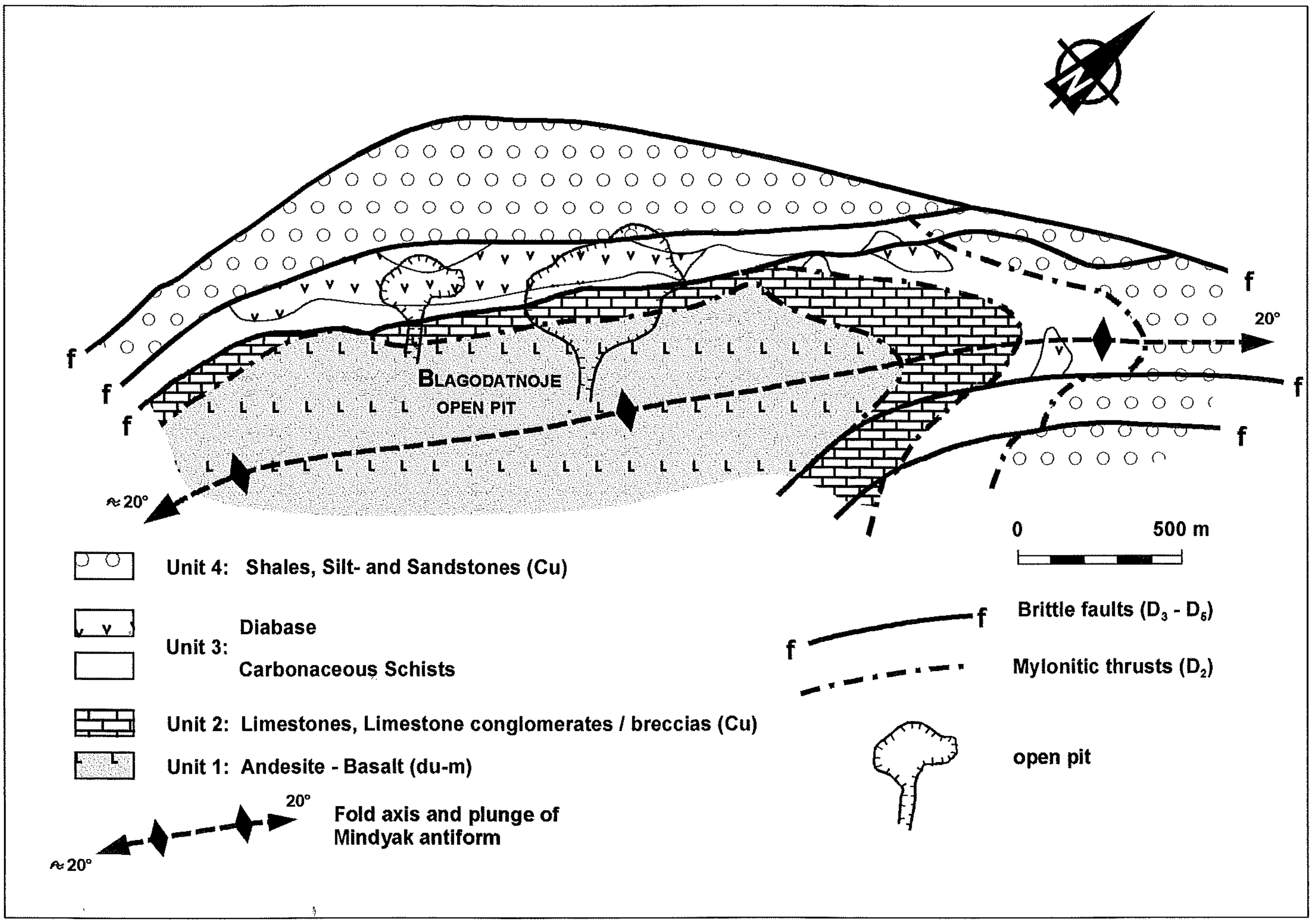


Fig. 3: Schematic geological map of the Mindyak ore field. Gold mineralization and mine workings are located on the overturned northwestern limb of the doubly plunging, NE-SW trending Mindyak antiform (note location of main open pits). Note the refolding of allochthonous units 1-4 by the Mindyak antiform and later faulting along NE-SW trending longitudinal faults

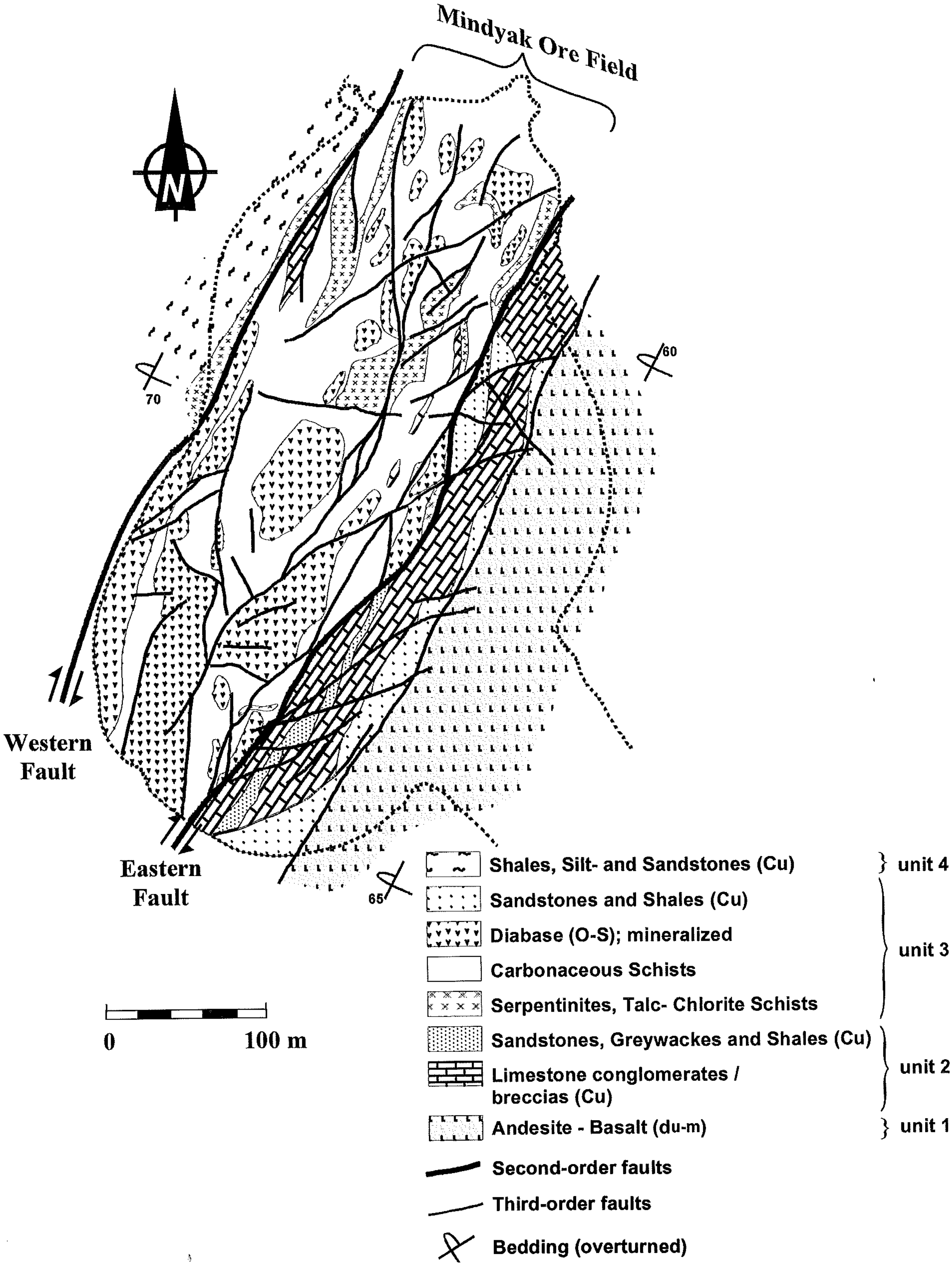


Fig. 4: Geological map of the main Blagodatnoje open pit from the central parts of the Mindyak ore field (compare Fig.3 for location) illustrating the structural and lithological controls of gold mineralization. The ore field is confined to the tectonic melange (unit 3) that is bounded by the NE-SW trending, second-order Western and Eastern Faults. Mineralization is controlled by third-order brittle faults that developed during dextral strike-slip reactivation of the longitudinal faults and their intersections with blocks of lower Paleozoic (O-S) diabase.

(Figs. 3 and 4). Third-order faults and, in particular, intersections between different fault sets largely control gold mineralization and the geometry of ore lodes (Seravkin et al., 1994). Third-order structures are composed of : (1) northerly to northeasterly trending, steep southeasterly dipping shear veins that are parallel to the bounding second-order faults; (2) easterly trending tension veins that dip at steep-to-moderate angles to the south and north; and (3) hybrid shear-tensional veins, which are northwest striking. Mutually cross-cutting relations among different vein sets are best reconciled with a single regional stress regime in which the maximum principal stress was oriented subhorizontally in an E-W direction. Ore shoots in the deposits may show distinct elongate shapes and down plunge extents locally exceeding 300 m.

The size of the ore fields is determined by the extent of the bounding second-order structures and the domains they enclose. The Mindyak and Murtekti ore fields show northeasterly strike extents of 1.2 and 2.5 km, respectively. The width of the ore fields ranges from 120 to 200 m at Mindyak (Figs. 3 and 4) to approximately 500 m at Murtekti.

Fault and vein textures

Most structures that control gold mineralization show features typical of brittle deformation, such as brittle fault gouges, fault and hydrothermal breccias, fracture networks and stockwork zones. The development of ductile deformation fabrics is largely confined to incompetent lithologies such as serpentinites and pelitic sediments (see below). Vein textures commonly comprise buck quartz, mosaic breccias, comb textures, open-space filling, and, to a lesser extent, ribbon textures. Most of these reflect vein formation at relatively low confining pressures and shallow crustal levels (i.e. 2-5 km). Superimposed textures such as later quartz- and quartz-carbonate brecciation and infills of earlier veins are common and indicate multistage hydrothermal activity during repeated reactivation of earlier vein structures.

Host rocks

The majority of host rocks are mafic-to-felsic volcanics and, to a lesser extent, volcaniclastics and sediments. The significance of volcanic rocks for gold mineralization can be attributed to: (1) competency contrasts between adjacent units; and (2) geochemically favourable lithologies for gold mineralization.

Mechanical controls and the importance of competency contrasts for fluid flow and mineralization are stressed by the occurrence of pervasive quartz-carbonate veining, brecciation, alteration and mineralization, preferably at the intersections between fault zones and specific lithologies. These lithologies are predominantly massively developed mafic and/or felsic volcanic rocks. At Murtekti, quartz-vein arrays, quartz-carbonate stockworks and gold mineralization are particularly well developed within and adjacent to felsic volcanic stocks. At Mindyak, veining, hydrothermal alteration and mineralization is most intense in blocks of massively developed diabase (Figs. 3 and 4).

Geochemical controls of gold mineralization are evident where mafic volcanics are hosts to gold mineralization. This is the case at the Mindyak deposit, where > 90 % of gold is derived from blocks of lower-Paleozoic diabase characterized by high Fe : (Fe + Mg) ratios (Seravkin et al., 1994; Ertl et al., 1997). Adjacent lithologies, such as comparably competent units of sandstones, cherts or blocks of diorite, show only subeconomic gold grades. It thus appears that the mafic volcanics are not only sites of extensive hydrothermal veining, but that they also represent geochemically favourable host rocks promoting sulphidation reactions leading to destabilization of gold reduced-sulphur complexes and concomittant gold precipitation.

The confinement of gold mineralization to mechanically and/or geochemically favourable host rocks also constrains the size of the deposits. Since host units are only of a limited lateral and vertical extent due to the highly tectonized nature of rock units in the mélange of the MUF and/or the primarily restricted size of intrusive dykes or stocks, most deposits along the MUF are only of relatively small size.

Mineralization, wall-rock alteration and geochemistry

Hydrothermal activity in the deposits involved multiple phases of veining and associated alteration and mineralization. Gold mineralization in most deposits is an integral part of wall- rock alteration. The ore mineralogy is commonly simple, with gold preferentially sited in sulphides such as pyrite and arsenopyrite that occur mainly as fracture fillings or disseminated in alteration halos around quartz-carbonate veins and breccias. Free gold occurs subordinately. Other sulphides include chalcopyrite, sphalerite, galena, and fahlores with minor amounts of pyrrhotite, enargite, and bornite (Seravkin et al., 1994). Local variations in the abundance of sulphides may occur on a deposit scale. At Mindyak pyrite predominates in the main mineralization zone in the northern parts of the deposit, whereas arsenopyite is abundant in the southern extension of the ore field. In most deposits there is clear evidence of multiple phases of mineralization and/or remobilization of gold, as is indicated by overlapping ore and alteration mineral parageneses (see below) confined to individual controlling structures, but that may also affect the entire ore fields. Most of these mineralization phases are likely to reflect a fluid continuum within the evolving fault zones, rather than discrete pulses of hydrothermal activity. However, a remobilization of metals, including gold, and sulphur from spatially associated polymetallic massive sulphide deposits has been suggested for the Murtekti ore field, which borders the large, mid-Paleozoic Uchaly massive sulphide deposit (Seravkin et al., 1994).

Wall-rock alteration generally comprises quartz, carbonate minerals (mainly dolomite, ankerite, and calcite), sericite, and chlorite, together with albite, fuchsite and, locally, graphite. The nature of wall-rock alteration is controlled by host-rock composition and prevailing P-T conditions during alteration. In felsic-to-intermediate volcanics, alteration is mainly characterized by sericitization, silicification, and carbonatization. In mafic host rocks, hydrothermal alteration is much more intense and the predominant style of alteration is carbonatization, in which Fe-Mg carbonates prevail in the inner alteration zones and grade laterally into calcite-dominated assemblages. In addition, silicification and chloritization are also widespread. Ultramafic units are typically altered to listvenites made up of quartz, carbonate, sericite, and fuchsite. However, listvenitization such as that observed at Mindyak may not be directly related to gold mineralization, representing a phase of alteration that predates the main ore-forming event (Sazonov, 1992; Seravkin et al., 1994). Irrespective of host-rock composition, the type of alteration and the mineral parageneses indicate lower greenschist-facies conditions, which is in agreement with the very low- to low-grade metamorphic grades of rocks in the MUF and the mainly brittle style of faulting and vein textures.

Wall-rock alteration commonly involves introduction of CO_2, K, S, and H_2O with either introduction or redistribution of SiO_2. There is a distinct enrichment of trace elements such as Cu, Pb, Ag, As, and Sb together with Au.

Fluid inclusions

Fluid inclusion data from gold deposits along the MUF are scarce. Fluid inclusions from quartz-carbonate veins in the Mindyak deposit are predominantly of a secondary nature, with subordinate primary and pseudosecondary inclusions. They are two-phase aqueous inclusions. During microthermometry, a clathrate phase was observed in some inclusions indicating the presence of minor amounts of CO_2, a feature consistent with the carbonatization of wall rocks. Apparent salinities are low (2-6 wt.% NaCl equiv.). Homogenization temperatures show a wide scatter and range from 250 to 400°C for primary and pseudosecondary inclusions. Evidence of boiling is locally preserved, but petrographic evidence, together with the fact that gold is almost exclusively sited in sulphides, implies that phase separation was not the main factor responsible for gold precipitation. Pressure estimates from fluid inclusions indicate a depth of formation of the mineralization at Mindyak of 2 to 3 km.

GOLD DEPOSITS IN THE EAST URALIAN ZONE

Nature of deposits

Gold deposits in the EUZ are spatially associated with upper-Devonian to lower-Carboniferous and Permian granitoids that typically form elongate, N-S trending composite massifs (Figs. 2 and 5). Gold mineralization occurs either within or adjacent to granitoid plutons. The former group includes the very large Kochkar mining district that has produced > 300 t Au in its 250 year mining history and the Novotroitsk deposit immediate south of Kochkar (Fig. 5). Both deposits are hosted by the lower-Carboniferous Plast massif and are characterized by vein-type morphologies, as well as subordinate disseminated types of mineralization. The latter comprise the Svetlinskoe deposit, located at the northern termination of the Permian Sanarsk massif and hosted in metavolcanosedimentary schists that form the envelope of the pluton, and the Rudny deposit that is situated at the northern tip of the lower-Permian Dzhabyk pluton (Fig. 2) and hosted in Silurian schists.

Average grades at Kochkar are 4-6 g/t Au, with locally mined high-grade ore shoots carrying ≥ 15 g/t. The overall extent of the Kochkar district is approximately 4 km along its easterly strike and the ore field extends for approximately 15 km in a N-S direction. Exploration and mining have identified a continuous down-dip extent of the mineralization to depths of > 1000 m. Current mining exploits levels between 500 and 700 m below surface at Kochkar and 200 to 430 m at Novotroitsk. In addition to underground operations at Kochkar and Novotroitsk, open-pit mining at Svetlinskoe is aimed at oxidized, low-grade ore zones with cut-off grades of around 1 g/t.

Structure

In contrast to the predominantly northerly-to-northeasterly trends of controlling structures along the MUF, gold mineralization in the EUZ is typically sited in easterly trending structures. Most of the gold deposits are hosted in dilational, or hybrid, tensional, shear-vein

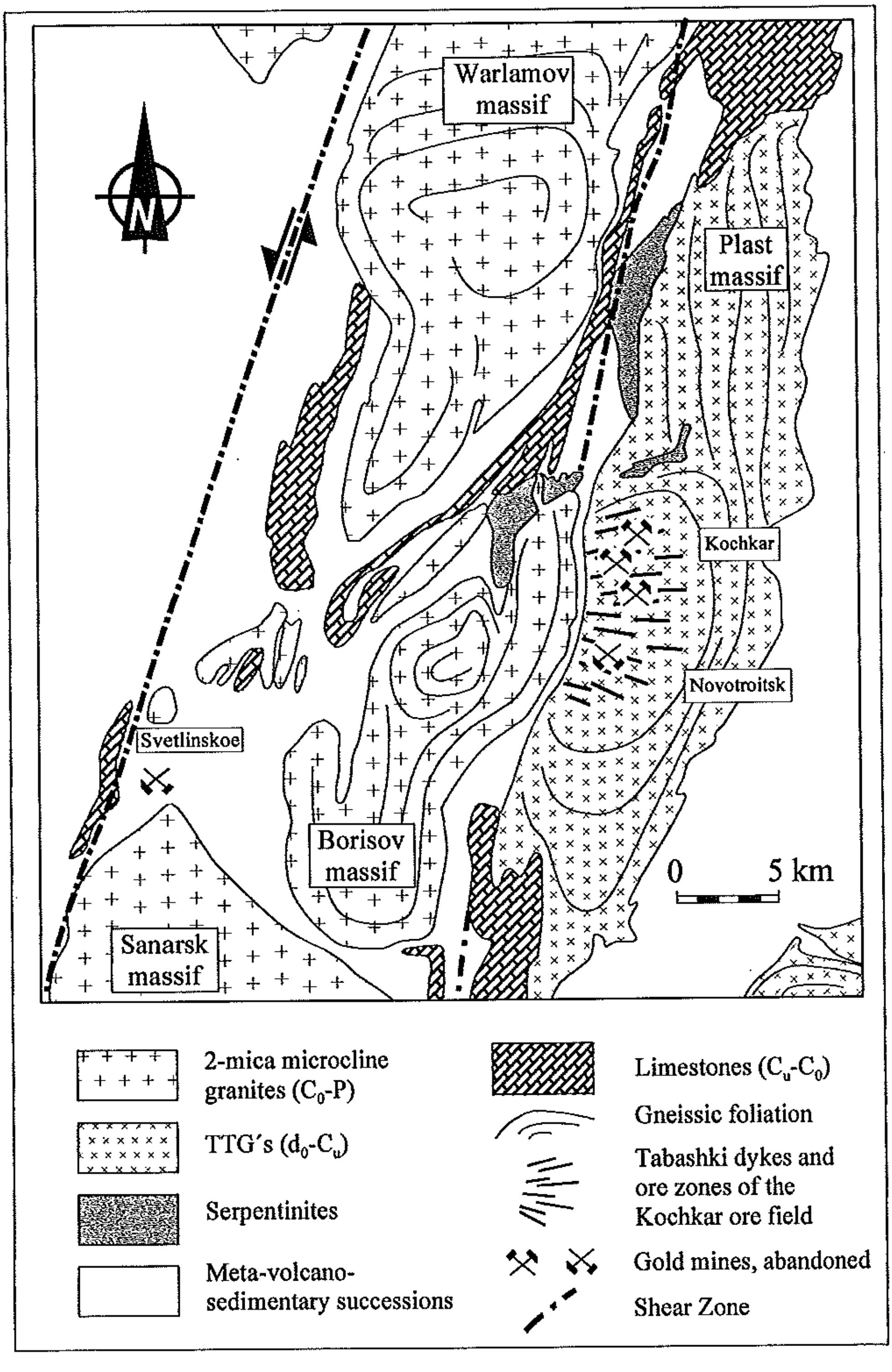


Fig. 5: Simplified geological map showing the distribution of the two main suites of late-Paleozoic granitoids in the East Uralian Zone around the Plast massif and associated gold mineralization and mine workings of the Kochkar district. Note the NNE trend of granitoids parallel to bounding shear belts and the distinctly E-W trend of ore controlling structures and dykes in the Plast massif. The Svetlinskoje deposit is located in the exocontact of the Sanarsk massif corresponding to a strain shadow position during E-W directed regional shortening.

systems that formed during E-W directed regional compression. Vein formation appears to be mainly controlled by competence contrasts between host rocks and enclosing wall-rock lithologies. This is also true for the giant (> 500 t Au) Beresovsk ore field in the middle Urals near the town of Ekaterinburg, where east-trending gold-quartz lodes, the so-called 'krassyk' veins, are confined to N-S trending granitic dykes that have intruded a complexely folded, lower-Paleozoic metavolcanosedimentary succession (Smirnov, 1976).

The E-W extent of ore-controlling structures in the EUZ is most prominently displayed in the Kochkar district (Fig. 5). Gold mineralization is confined to a conjugate set of NE- and SE- trending, steep northerly and southerly dipping, tabular-shaped gold-quartz lodes that are spatially closely associated with mafic-to-intermediate dykes that define a somewhat radial outcrop pattern (Fig. 4). Over 2000 of these dykes have been mapped in the Plast massif and are collectively referred to as 'Tabashki' (see below). Most of the dykes terminate abruptly against the enveloping metavolcanosedimentary schists indicating marked rheological contrasts between granitoids and relatively incompetent schists.

Gold is currently mined from three zones in the Kochkar district, termed the northern, central and southern zones. These zones represent NE- to ENE-trending corridors characterized by a particularly high abundance of closely spaced dykes and associated mineralization. Quartz veining and associated gold-sulphide mineralization mainly occurs in three different positions relative to the Tabashki dykes (Fig. 6), namely : (1) along the margins of the dykes in contact with enveloping granodiorites; (2) to a lesser extent within the dykes; and (3) subordinately within granodiorites without an apparent spatial association with Tabashki dykes. In the latter case, granitoids are intensely altered (see below) and strongly schistose. The composite ore zones are made up of *en echelon* quartz lodes. Individual quartz lodes show strike lengths of up to 500 m attaining average widths of 1 m (0.2 to 6 m).

Ribbon textures and sigmoidally folded, *en echelon* quartz veins testify to silicification and associated gold mineralization in shear zones developed adjacent to and within the dykes. Shearing was evidently controlled by strain refraction into the mafic, biotite-rich dykes that represent relatively incompetent lithologies compared to enclosing, feldspar-rich granitoids. Evidence of shear localization in dykes is preserved in the form of mylonitic fabrics and intrafolial folding, as well as transposition of quartz veins into the shear fabric contained within the dykes. Strain refraction and non-coaxial deformation within dykes has evidently promoted fracturing of brittle granitoids which allowed access of fluids and resulting silicification, sulphide mineralization and precipitation of gold. Later, E-W trending dykes cut earlier dykes and associated gold-quartz lodes at low angles indicating that both the emplacement of dykes, deformation and associated alteration and mineralization occurred in an E-W directed regional stress field. The radial distribution of dykes and associated gold-quartz lodes normal to the western contact of the Plast massif (Fig. 5), with granitoids of the Borisov massif situated to the west, indicates that the external geometry of the Plast massif has most likely influenced the local stress field superimposed onto the far-field stress regime.

The Svetlinskoje (Fig. 5) and Rudny (Fig. 2) deposits occur in the exocontact of the Sanarsk and Dzhabyk plutons, respectively. Both deposits occur in schists at the northern terminations of the granitoid massifs. Mineralization is of a disseminated type at Svetlinskoe, but the deeply weathered nature of the Svetlinskoe deposit precludes an interpretation of the structural controls of mineralization. Mineralization at Rudny occurs in three subvertical, pipe-like stockwork zones that are mined for gold and piezo-quartz crystals.

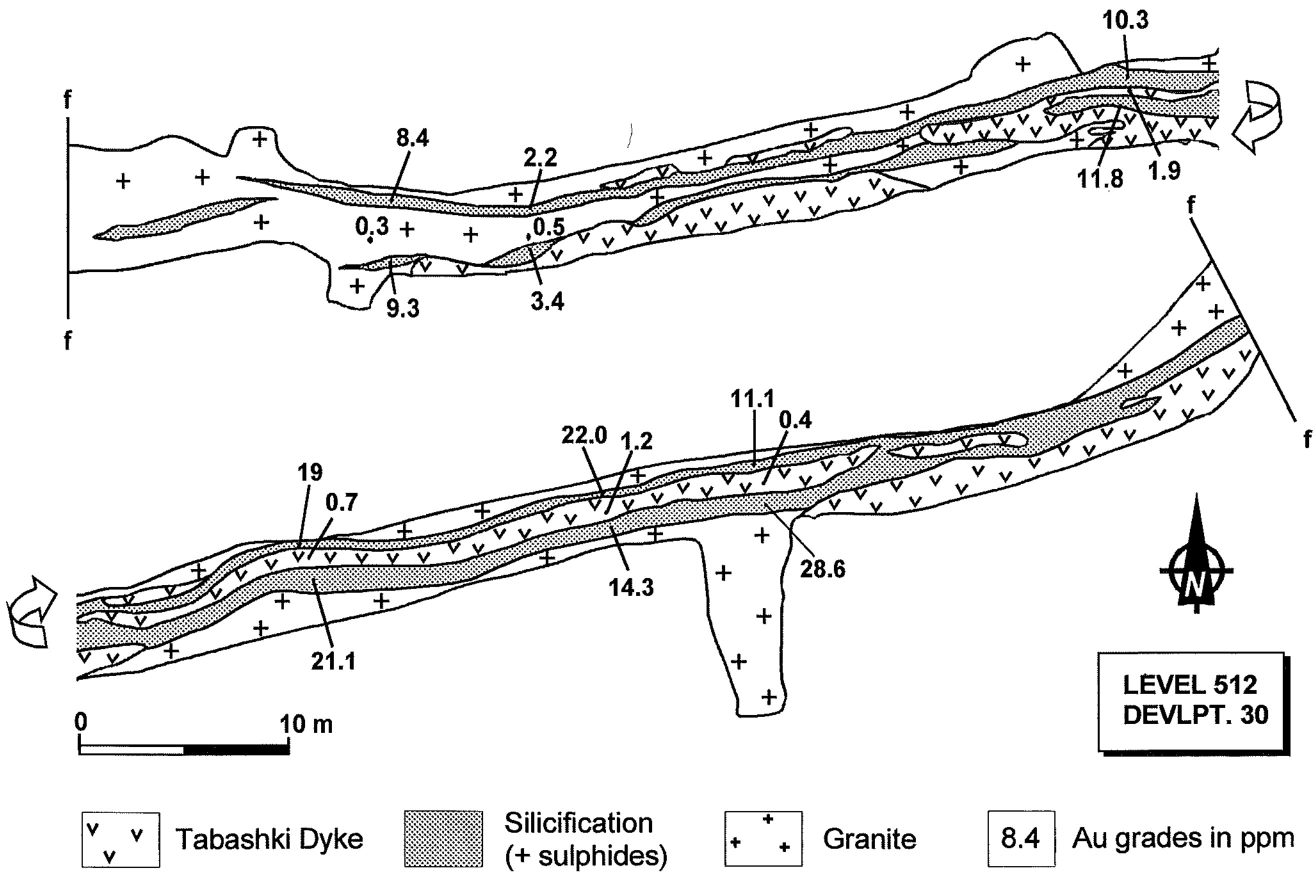


Fig. 6: Detailed map of an underground development of the Kochkar Mine (512 level, development 30) illustrating the spatial relationship between gold-quartz lodes, Tabashki dykes and enveloping granitoids. Note that silicification and associated gold mineralization are preferably developed along the contact between the sheared Tabashki dyke and surrounding granitoids. Brittle fracturing in the competent granitoids during shearing in biotite-rich Tabashki dykes allowed for the access of fluids and associated gold-quartz mineralization

Mineralization and wall-rock alteration

Alteration adjacent to gold-quartz lodes at Kochkar and Novotroitsk is characterized by a pervasive silicification and sericitization of wall-rock granitoids, and is commonly accompanied by the development of a vein-parallel foliation in adjacent granitoids. Tourmaline is locally present and scheelite forms part of the alteration assemblage, particularly in the central parts of the Kochkar district. The presence of both aligned and random sericite/muscovite in alteration zones around quartz lodes indicates that the main deformation and associated mineralization ended close to the peak of regional metamorphism. In Tabaski dykes, mylonitic, biotite-dominated fabrics are similarly overprinted by late-to-postkinematic poikiloblastic biotite, greenish-blue hornblende and zoisite. Gold-sulphide mineralization was locally remobilized. A later alteration stage is indicated by chloritization of mafic minerals and quartz and carbonate veining.

Gold is fine grained (commonly < 20 μm) and occurs predominantly as specks of free gold in quartz. Sulphides comprise mainly pyrite and arsenopyrite with subordinate chalcopyrite, sphalerite, fahlores, galena, and bismuthinite. Approximately 20 % of gold is associated with sulphides. The fineness of gold is commonly > 875 (Smirnov, 1976). On a district scale, there are considerable variations in the volumetric abundance and relative proportions of sulphide minerals. While gold-quartz veins at Kochkar contain only 2-7 vol.% sulphides (mainly pyrite), mineralization at Novotroitsk is characterized by abundant sulphide mineralization (up to 60 vol. % in veins) and a predominance of arsenopyrite.

Metamorphism

Metavolcanosedimentary schists surrounding the granitoids comprise mineral assemblages that suggest upper-greenschist to mid-amphibolite facies metamorphic grades. Late kinematic mineral assemblages contained in the Tabashki dykes (i.e. biotite-amphibole-zoisite) indicate amphibolite-facies conditions during peak metamorphism that have evidently outlasted this phase of mineralization. Some workers relate the Permian metamorphism to the emplacement of large granite plutons into rocks of the EUZ (e.g. Smirnov, 1976), while others attribute the metamorphism to regional-scale burial during Permian crustal shortening and overthrusting of the EUZ.

DISCUSSION

Table 2 summarizes the general geological characteristics of lode-gold deposits in the central South Urals emphasizing distinct differences in structural controls, host rocks, metamorphic grade, conditions of mineralization, and timing of gold mineralization along the MUF and in the EUZ. A late kinematic timing of lode-gold deposits such as those along the MUF is recorded from many late-Archaean and Phanerozoic lode-gold districts where accurate radiometric age dating has identified the precise timing of hydrothermal events relative to the tectonometamorphic evolution of terranes (Nesbitt, 1990; Kerrich and Cassidy, 1994; Miller et al., 1994). Recent models that address the timing of fluid production and fluid discharge with respect to the tectonic, metamorphic and magmatic evolution of lode-gold provinces can be grouped into two main schools of thought. Goldfarb et al. (1991) related the late kinematic and metamorphic timing of gold-quartz veins in the Alaskan cordillera to devolatilization reactions in the deeper crust during subduction. However, upward fluid flow is envisaged to have been initially hampered due to the compressional tectonics maintaining low permeabilities within the metamorphic pile, and unsuitably orientated low-angle structures. Large-scale fluid discharge to shallower crustal levels was triggered by a shift in tectonic regime, associated uplift, stress relaxation and the formation of suitably inclined fault structures that could tap pressurized fluid reservoirs at depth. Stüwe et al. (1993) and Stüwe (1998) closely related fluid production to the tectonometamorphic evolution of terranes. Crustal thickening and accompanying denudation causes metamorphism to occur later at depth than at shallow levels, so that peak metamorphism at deeper levels may produce fluids that are precipitated as 'postmetamorphic' quartz veins at shallower crustal levels ('deep-late type of metamorphism'). In contrast, terranes characterized by magmatic heating as a result of underplating or mid-crustal plutonism

Table 2 : Comparison of the geological situation, structural controls, host rocks, and styles of mineralization and alteration of gold deposits along the Main Uralian Fault and in the East Uralian Zone

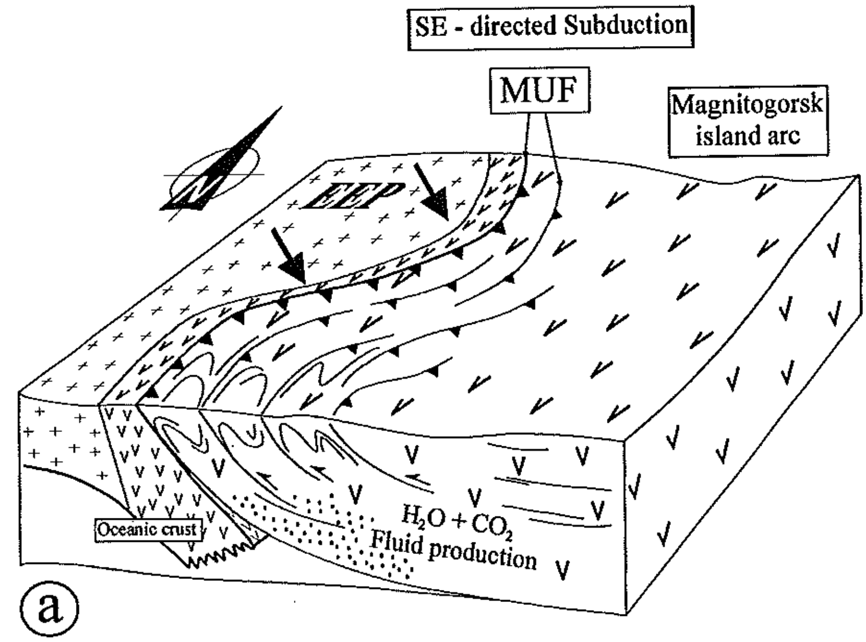
	MAIN URALIAN FAULT	*EAST URALIAN ZONE*
Size of deposits	- small (< 1 t Au) to medium (30-50 t Au)	- small (< 1 t Au) to very large (> 300 t Au)
Host rocks	- mainly mafic volcanic rocks, subordinately felsic vocanics, sediments, and ultramafics	- predominantly granitoids, subordinately schists (but commonly in proximity to granitoid plutons)
Metamorphism	- sub- to lower-greenschist facies grades	- upper-greenschist to amphibolite-facies grades
Structural controls	- mineralization controlled by northerly-trending second- and third-order structures and fault intersections - brittle faults, hydraulic breccias	- mainly in composite granitoids, controlled by ductile-brittle easterly-trending extensional and/or hybrid tensional-shear veins; - in exocontact of granitoids in strain shadow positions - ductile-brittle shear zones, ribbon-quartz textures
Relation to plutonic rocks	- no evidence for plutonic activity	- very close spatial and possibly genetic relation to granitoid plutons and intrusive dykes
Ore morphology and textures	- tabular- to pipe-like lodes, also disseminated mineralization - vuggy quartz, hydrothermal breccias	- tabular, vertically continuous lodes; occasionally disseminated - buck quartz, ribbon textures
Alteration	- carbonatization, silicification, chloritization, sericitization	- silicification, sericitization
Timing	- late-kinematic, upper Permian to lower Triassic	-synkinematic; lower-to-mid-Permian
Tectonic position	- along first-order terrane boundary	- in accreted, deformed and metamorphosed island-arc to back-arc terrane of the orogenic hinterland

reach peak metamorphic conditions earlier at depth that at shallow levels ('deep-early type of metamorphism'). The time gap between metamorphism and fluid infiltration at different crustal levels is estimated to be as much as 50 Ma in individual orogenic belts (Stüwe, 1998).

Lode-gold mineralization along the MUF

On a regional scale, the main ore fields of the Mindyak and Murtekti districts are located in a part of the MUF where the first-order fault zone defines a distinctly NE-SW trend compared to the overall N-S strike extent of the fault. This deflection is controlled by the geometry of the Ufimian Amphitheatre, which forms a wedge-shaped protrusion of the East European Platform into the internides of the middle Urals (Figs. 2 and 7b). It is not clear whether extensive fluid circulation has affected other parts of the MUF, but the lack of prominent gold deposits elsewhere suggests a restriction of large-scale hydrothermal activity to this zone. Moreover, structurally controlled fluid flow and gold mineralization in this part of the MUF coincide with a shift from convergent to predominantly transcurrent tectonics. The change in stress regime may be related to changes in plate motion during the final docking phase and amalgamation of terranes. Dextral transcurrent shearing that is particularly well developed along the NE-SW trending portions of the MUF possibly corresponds with the development of the second- and third-order controlling structures as lateral accommodation structures formed by the eastward indentation of the Ufimian Amphitheatre during the final stages of terrane docking (Fig. 7a,b).

At this stage, a detailed interpretation of the origin and timing of gold mineralization cannot be made until radiometric age determinations as well as fluid inclusion and stable isotope data of vein and ore minerals are available. A tentatively suggested scenario for the formation of lode gold deposits along the MUF combines the models presented by Goldfarb et al. (1991) and Stüwe (1998) for the development of late-kinematic gold-quartz veins in metamorphic terranes. Vein-forming fluids were generated during devolatilization of subducted crust and/or metamorphic dewatering during prograde metamorphism of the basal parts of the MUF (Fig. 7a). Metamorphism, following thickening and denudation at surface, is dependent on heat conduction across the crust and, since thermal equilibration will be rather slow, peak metamorphic conditions and associated devolatilization at depth will occur later than at shallow levels (Stüwe, 1998). In addition, upward migration of fluids was likely to have been hampered by the compressional tectonic regime, the relatively unsuitable orientation of low-angle thrusts and, most importantly, the presence of impermeable layers within the lithologically heterogeneous mélange zone. Impermeable lithologies may include upper-Paleozoic pelitic metasediments that form a common constituent of the MUF. Consequently, fluids might have ponded at depth and not released until suitably oriented permeability pathways were created. Fluid conduits are represented by steeply inclined strike-slip faults that formed during reactivation of earlier compressional structures (Fig. 7b). It should be emphasized, however, that since lode-gold deposits along the MUF have formed at relatively shallow crustal levels, it is likely that meteoric fluids will have contributed to the ore-forming process. A magmatic source for fluids is considered unlikely, since late-kinematic plutonism is not recorded along the MUF in the central South Urals.



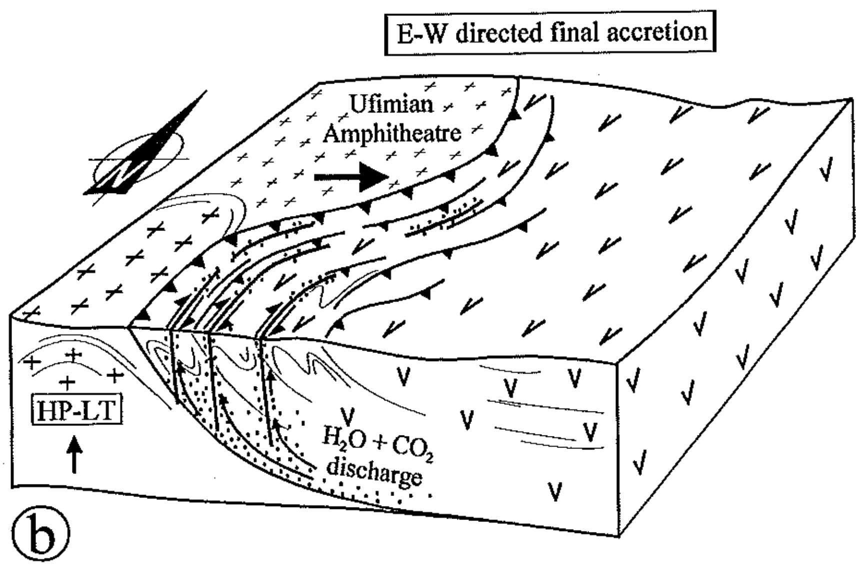


Fig. 7: Synoptic sketch diagram of the evolution along the Main Uralian Fault, illustrating (a) generation of vein-forming fluids through devolatilization of subducted crust during convergence (EEP: East European Platform). Compressional tectonics maintained low crustal permeabilities and the predominantly shallow attitude of structures and the presence of pelitic units along the MUF inhibited fluid release. Note: in this sketch, an oblique collision is assumed. (b) A shift to E-W directed compression during the final docking of terranes initiated dextral strike-slip motion along the southern margins of the Ufimian Amphitheatre and allowed hydrothermal fluids to ascend rapidly through the steeply inclined conduits accompanying uplift and stress relaxation.

Lode-gold deposits in the EUZ

The precise timing of gold mineralization in the EUZ is poorly constrained, since radiometric age data are scarce or often controversial (e.g. Sazonov et al., 1989). For the Kochkar and Novotroitsk deposits, a lower age limit of the mineralization is provided by the lower-Carboniferous (360-320 Ma; Smirnov, 1976) emplacement of the composite Plast massif. Since gold mineralization and related alteration have evidently occurred close to peak metamorphic conditions during Permian tectonism and metamorphism, gold mineralization must have formed between upper-Carboniferous and mid-Permian times. Timing of gold mineralization thus corresponds with the onset of the main phase of compressional tectonics in the EUZ and is temporally associated with a major phase of granitic plutonism.

The structural controls of lode-gold deposits in the EUZ by predominantly conjugate NE- and SE- trending hybrid tensional-shear structures is in agreement with gold mineralization during the main phase of E-W directed compressional tectonics. The confinement of gold-controlling structures to granitoids such as at Kochkar and Novotroitsk indicates that competence contrasts between massively developed plutons and surrounding metavolcanosedimentary schists have provided structural sites and loci for regional-scale fluid flow. Gold mineralization hosted in enveloping schists outside granitoid plutons, such as at Svetlinskoe and Rudny, are located preferably at the (northern) terminations of granitic massifs, zones corresponding to strain shadow positions during E-W regional shortening. The emplacement of voluminous mid- to upper-crustal granitoid massifs is indicative of a markedly different tectonometamorphic evolution of the EUZ compared to that of the MUF, being characterized by presumably higher geothermal gradients due to the 'external' heat input during plutonism. Consequently, highest metamorphic grades at depth are reached earlier than at shallow levels, corresponding to the 'deep-early' type of metamorphism after Stüwe et al. (1993). Devolatilization and fluid generation at depth would thus occur early during the tectonometamorphic development of the terrane, which is in accordance with the structural controls and the largely synmetamorphic timing of gold-quartz lodes.

CONCLUSIONS

Geologic relationships in the southern Urals suggest that gold mineralization occurred during two distinct stages, separated by 30-50 million years, in two different tectonostratigraphic zones, namely the Main Uralian Fault and the East Uralian Zone.

Gold deposits along the Main Uralian Fault are developed along late-kinematic transcurrent fault zones within and adjacent to mechanically and geochemically favourable host rocks such as mafic and subordinately felsic volcanics. Fluid inclusions and alteration mineral parageneses indicate shallow crustal conditions for ore formation, which is consistent with the very low grade of metamorphism of host rocks and brittle style of faulting and vein textures. Overprinting relationships between metamorphic and alteration mineral parageneses indicate that mineralization occurred late- to post-peak metamorphism. Transcurrent shearing along the first-order structure followed a period of thrust imbrication and crustal thickening and can be correlated with a shift in tectonic regime from initial compressional and/or transpressional tectonics, during the main phase of subduction and plate convergence, to an E-W directed final docking and lateral adjustment of terranes in the upper-Permian to lower-Triassic (Fig. 7a,b). In contrast, relationships between alteration and later metamorphic mineral parageneses in most of the gold deposits of the East Uralian Zone suggest a lower- to mid- Permian timing of gold mineralization during the major phase of E-W directed compressional tectonics close to peak-metamorphic conditions. Here, gold mineralization is spatially and temporally associated with granitoid massifs that represented competent bodies during regional deformation. The apparent time gap of regional-scale fluid discharge and gold mineralization in different zones of the Urals is tentatively explained by a different tectonic, metamorphic, and magmatic evolution of these zones.

Radiometric age constraints and stable isotope data are still needed in order to place precise constraints on the timing and origin of gold mineralization in the southern Urals. However, the preservation of the original collisional architecture of the orogen provides an ideal opportunity to study the spatial and temporal relationships between sites of fluid generation, the geometry and distribution of fluid pathways and the timing of discrete fluid discharge events with respect to regional-scale tectonic, magmatic and metamorphic events in collisional orogens.

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